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HIGH VOLTAGE DESIGN GUIDE: AIRCRAFT

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This report supplies the theoretical background and design techniques needed by an engineer who is designing electrical insulation for high-voltage, high-power components, equipment, and systems for aircraft. A literature survey and abundant bibliography identify references that provide further data on the subjects of partial discharges, corona, field theory and plotting, voids and processes for applying insulation. Both gaseous and solid insulations are treated. Cryogenic and liquid design notes are included.

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Tests and test equipment for high voltage insulation and equipment are defined. Requirements of test plans and procedures for high-voltage, high-power equipment are identified and illustrated by examples.

Suggestions for high-voltage specifications are provided. Very few of the Military and Government specifications deal with system voltages above 10kv, thus most aircraft high-voltage specifications will have to be derived from the power industry specifications and standards produced by ASTM, IEEE, and NEMA.

This report is a revision of the High Voltage Design Guide for Airborne Equipment documented (AFAPL-TR-76-41) which reflects the finding of the High Voltage Testing portion of the program and an updated literature search.

FOREWORD

Presented herein is the Boeing Aerospace Company's Final Report covering work accomplished on Contract F33615-79-C-2067 for the period of September 29, 1979 through January 5, 1983. This contract is being performed for the Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson AFB, Ohio. The program is under the technical direction of Daniel Schweickart, AFWAL/POOS-2.

Personnel participating in this work for the Boeing Aerospace Company were W. G. Dunbar, the technical leader, and S. W. Silverman, the program manager.

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1.0 PROGRAM OBJECTIVES

The objectives of this program are as follows:

a. Perform high voltage tests on capacitors, cable assemblies and parts, and coils.

b. Design, fabricate, and evaluate a high voltage standard test fixture to be used for measuring the void content in various high voltage insulation systems.

c. Specify and procure a 150 kV, 400 Hz power supply for partial discharge measurements.

d. Update the Tests and Specifications Criteria Documents completed in U.S. Air Force Contract F33615-77-C-2054 to include the findings from the test article evaluations.

e. Develop a high voltage generator test procedure.

f. Update the Airborne High Voltage Design Guide completed on U.S. Air Force contract F33615-76-C-2008.

g. Develop a Spacecraft High Voltage Design Guide.

2.0 SCOPE

The major task reported in this volume is to:

- Update the Airborne High Voltage Design Guide document completed on U.S. Air Force Contract F33615-76-C-2008 based on the findings of the program and a literature search.

3. INTRODUCTION

One of the new challenges to the electrical insulation design engineer is the application of materials to high-voltage, high-power aircraft components. In aircraft, the space and volume constraints require that the high-power components be miniaturized, yet be compatible with the airplane's thermal and mechanical environment. Added to these constraints and requirements are the traditional demands for minimizing weight with less insulation and less metal, and at the same time keeping costs realistic.

There can be no miracle insulation that has ideal electrical, thermal, and structural properties. Therefore, the insulation engineer must recognize that each application has its own set of optimum insulations that satisfy all the electrical performance, environmental, and structural constraints. For example, capacitors require materials with high dielectric constants, whereas insulators and feedthroughs require good structural properties with low dielectric constant. For insulation applications other than capacitors, a low dielectric constant is generally preferred because it has low charging current. Insulators for solid state devices have a different and unique requirement --- a heat transfer rate which is usually not associated with low electrical conductivity. These examples show that the design engineer is always evaluating compromises when choosing electrical insulation.

An insulation, before being adopted, should be evaluated by test. Tests should include: (1) temperature cycling in the atmosphere in which it is to be operated, (2) high voltage evaluation, (3) measurement of dielectric constant and loss factor, (4) verification of tracking characteristics, (5) surface resistivity measurements, (6) voltage breakdown measurement, (7) development of models configured to represent the application, otherwise the effects of mechanical stress and the environments will not be correctly tested, (8) exposure to environment, and (9) application of mechanical stresses. These tests will provide some assurance of reduced infant mortality of the final assembly.

3.1 <u>Definition of "Insulation"</u>. The purpose of electrical insulation is to physically separate the electromagnetic field boundaries. The insulation

must be composed of materials which have very high resistivity in order to restrict the flow of leakage current between conductors.

Gaseous, liquid, and solid insulations are in use. An insulation system may consist of a single material, a composite structure such as a laminate, or a combination of materials like a cable insulation system having layers of different materials. Electrical insulation encompasses the terms "dielectrics" and "insulators." A "dielectric" is a discrete material or class of material with a high resistivity. It is a non-metal used for isolating electrodes. An "insulator" is a generic expression for a solid material used to mechanically support and electrically isolate one or more conducting elements.

3.2 <u>Design Guide Content</u>. Field theory and theoretical aspects of a gaseous breakdown, insulating materials, and high-voltage applications are comprehensibly treated in textbooks and technical papers. Applicable portions of this theory will be reviewed, and references where further detail can be found will be noted.

Much of this document is devoted to design techniques associated with electric fields. Partial discharges caused by the inclusion of voids in dielectrics is treated --- application as well as the theoretical aspects of a perfect hole embedded in an ideal block of insulation is discussed. The effects of external gas pressure and of the gas content within the voids is also discussed for specific applications.

Electric properties of insulation are discussed. Specifically, (1) dielectric strength, (2) resistance to corona, creepage and tracking, (3) voltage gradients generated between various electrode configurations, and (4) the utilization factors plotted for the most common electrode configurations. All these data are useful for quick preliminary evaluations of insulation designs.

One of the last two sections in this guide describes testing, test equipment, and the use of incipient failure detection devices. The other section lists common failure mechanisms associated with equipment insulation and possible solutions. Sources of more detailed data and analytical techniques are cited throughout the text.

3.3 GLOSSARY

Adsorption. The adhesion of gas or liquid molecules to the surfaces of solids or liquids with which they are in contact.

Aging. The change in properties of a material with time under specific conditions.

Alternating Current, Current in which the charge-flow periodically reverses and is represented by: $I=I_0\cos(2\pi ft+\phi)$ where I is the current, I_0 is the amplitude, f the frequency, ϕ the phase angle.

Ambient Temperature. The temperature of the surrounding cooling medium, such as gas or liquid, which comes into contact with the heated parts of the apparatus.

Anode. The electrode through which a direct current enters the liquid, gas, or other discrete part of an electrical circuit; the positively charged pole of an electrochemical cell.

Anti-Oxidant. Substance which prevents or slows down oxidation of material exposed to air.

Arcover Voltage. The minimum voltage required to create an arc between electrodes separated by a gas or liquid insulation under specified conditions.

Arc Resistance. The time required for an arc to establish a conductive path in a material.

Askarel. Synthetic liquid dielectric which is non-flammable.

Bond Strength. The amount of adhesion between bonded surfaces.

Breakdown (Puncture). A disruptive discharge through insulation.

Breakdown Voltage. The voltage at which the insulation between two conductors will break down.

Capacitance (Capacity). That property of a system of conductors and dielectrics which permits the storage of electricity when potential difference exists between the conductors. Its value is expressed as the ratio of a quantity of electricity to a potential difference. A capacitance value is always positive. The charge which must be communicated to a body to raise its potential one unit, represented by $C=Q/V$, where C is the capacitance, Q the quantity of charge, and V the potential. In a parallel plate condenser

$$C = \frac{KA}{d}$$

where A is the area of the plates, d the distance between them, and K the dielectric constant of the medium.

Capacitor (Condenser). A device, the primary purpose of which is to introduce capacitance into an electric circuit.

Cathode. The electrode through which an electric current leaves a liquid, gas, or other discrete part of an electric current; the negatively charged pole of an electrochemical cell.

Cavity. Depression in a mold.

Cell. A single unit capable of serving as a d-c voltage source by means of transfer of ions in the course of a chemical reaction.

Charge. In electrostatics, the amount of electricity present upon any substance which has accumulated electric energy.

Conductance. The reciprocal of resistance. It is the ratio of current passing through a material to the potential difference at its ends.

Conductivity. Reciprocal of volume resistivity. Conductance of a unit cube of any material.

Conductor. An electrical path which offers comparatively little resistance. A wire or combination of wires not insulated from one another, suitable for carrying a single electric current.

Contaminant. An impurity or foreign substance present in a material which affects one or more properties of the material.

Corona. A luminous discharge due to ionization of the gas surrounding a conductor around which exists a voltage gradient exceeding a certain critical value. A type of discharge--sometimes visible--in the dielectric of an insulation system caused by an electric field and characterized by the rapid development of an ionized channel which does not completely bridge the electrode. May be continuous or intermittent. Not a materials property, but related to the system, including electrodes.

Corona resistance. The time that insulation will withstand a specified level field-intensified ionization that does not result in the immediate complete breakdown of the insulation.

Corrosion. Chemical action which causes destruction of the surface of a metal by oxidation or chemical combination.

Coulomb. Unit quantity of electric charge; i.e., the quantity transferred by 1 ampere in one second.

Creep. The dimensional change with time of a material under load.

Creepage. Electrical leakage on a solid dielectric surface.

Creepage surface on path. An insulating surface which provides physical separation as a form of insulation between two electrical conductors of different potential.

Critical Voltage (of gas). The voltage at which a gas ionizes and corona occurs, preliminary to dielectric breakdown of the gas.

Delamination. The separation of layers in a laminate through failure of the adhesive.

Dielectric. (1) Any insulating medium which intervenes between two conductors and permits electrostatic attraction and repulsion to take place across it. (2) A material having the property that energy required to establish an electric field is recoverable in whole or in part, as electric energy.

Dielectric Adsorption. That property of an imperfect dielectric whereby there is an accumulation of electric charges within the body of the material when it is placed in an electric field.

Dielectric Constant (permittivity or specific inductive capacity). That property of a dielectric which determines the electrostatic energy stored per unit volume for unit potential gradient. The dielectric constant of a medium is defined by ε in the equation

$$F = \frac{QQ'}{4\pi\varepsilon r^2}$$

where F is the force of attraction between two charges Q and Q' separated by a distance r in a uniform medium.

Dielectric Loss. The time rate at which electric energy is transformed into heat in a dielectric when it is subjected to a changing electric field.

Dielectric Loss Angle (dielectric phase difference). The difference between ninety degrees (90°) and the dielectric phase angle.

Dielectric Loss factor (dielectric loss index). The product of its dielectric constant and the tangent of its dielectric loss angle.

Dielectric Phase Angle. The angular difference in phase between the sinusoidal alternating potential difference applied to a dielectric and the component of the resulting alternating current having the same period as the potential difference.

Dielectric Power Factor. The cosine of the dielectric phase angle (or sine of the dielectric loss angle).

Dielectric Strength. The voltage which an insulating material can withstand before breakdown occurs, usually expressed as a voltage gradient (such as volts per mil).

Dielectric Test. Tests which consist of the application of a voltage higher than the rated voltage for a specified time for the purpose of determining the adequacy against breakdown of insulating materials and spacings under normal conditions.

Dispersion. Finely divided particles in suspension in another substance.

Displacement Current. A current which exists in addition to ordinary conduction current in a-c circuits. It is proportional to the rate of change of the electric field.

Disruptive Discharge. The sudden and large increase in current through an insulation medium due to the complete failure of the medium under the electrostatic stress.

Dissipation Factor (loss tangent, tan δ, approx. power factor). The tangent of the loss angle of the insulating material.

Electric Field Intensity. The force exerted on a unit charge. The field intensity E is measured by

$$E = \frac{q}{4\pi\varepsilon r^2}$$

where r is the distance from the charge q in a medium having a dielectric constant ε.

Electric Strength (dielectric strength)(disruptive gradient). The maximum potential gradient that the material can withstand without rupture. The value obtained for the electric strength will depend on the thickness of the material and on the method and conditions of test.

Electrode. A conductor, not necessarily metal, through which a current enters or leaves an electrolytic cell, arc, furnace, vacuum tube, gaseous discharge tube, or any conductor of the non-metallic class.

Electromagnetic Field. A rapidly moving electric field and its associated moving magnetic field, located at right angles both to the electric lines of force and to their direction of motion.

Electron. That portion of an atom which circles around the center, or nucleus. An electron possesses a negative electric charge, and is the smallest charge of negative electricity known.

Encapsulating. Enclosing an article in a closed envelope of plastic.

Energy of a Charge. $W = \frac{1}{2}QV$, given in ergs when the charge Q and the potential V are in electrostatic units.

Energy of the Electric Field. Represented by $W = KE^2$ where E is the electric field intensity in electrostatic units, K the specific inductive capacity, and the energy of the field E in ergs per cm^3.

Epoxy Resins. Straight-chain thermoplastics and thermosetting resins based on ethylene oxide, its derivatives or homologs.

Farad. Unit of capacitance. The capacitance of a capacitor which, when charged with one coulomb, gives a difference of potential of one volt.

Fiber. A thread or threadlike structure such as comprises cellulose, wool, silk, or glass yarn.

Fibre. A specific form of chemically gelled fibrous materials fabricated into sheets, rods, tubes, and the like.

Filler. A substance, often inert, added to a plastic to improve properties and/or decrease cost.

Flame Resistance. Ability of the material to extinguish flame once the source of heat is removed.

Flammability. Measure of the material's ability to support combustion.

Flashover. A disruptive discharge around or over the surface of a solid or liquid insulator.

Frequency. The number of complete cycles or vibrations per unit of time.

Graded Insulation. Combination insulations with the portions thereof arranged in such a manner as to improve the distribution of the electric field to which the insulation combination is subjected.

Gradient. Rate of increase or decrease of a variable magnitude.

Grounded Parts. Parts which are so connected that, when the installation is complete, they are substantially of the same potential as the earth.

Ground Insulation. The major insulation used between a winding and the magnetic core or other structural parts, usually at ground potential.

Hall Effect. The development of a potential difference between the two edges of a strip of metal in which an electric current is flowing longitudinally, when the plane of the strip is perpendicular to a magnetic field.

Hardener. A substance or mixture of substances added to plastic composition, or an adhesive to promote or control the curing reaction by taking part in it.

Heat Sink. Any device that absorbs and draws off heat from a hot object, radiating it into the surrounding atmosphere.

Hertz. (Hz) A term replacing cycles-per-second as an indication of frequency.

Hygroscopic. Tending to absorb moisture.

Hysteresis. An effect in which the magnitude of a resulting quantity is different during increases in the magnitude of the cause than during decreases due to internal friction in a substance and accompanied by the production of heat within the substance. Electric hysteresis occurs when a dielectric material is subjected to a varying electric field as in a capacitor in an alternating-current circuit.

Impedance. The total opposition that a circuit offers to the flow of alternating current or any other varying current at a particular frequency. It is a combination of resistance R and reactance X, measured in ohms and designated by Z. $Z = (R^2 + X^2)^{1/2}$.

Impregnate. To fill the voids and interstices of a material with a compound. (This does not imply complete fill or complete coating of the surfaces by a hole-free film).

Impulse. A unidirectional surge generated by the release of electric energy into an impedance network.

Impulse Ratio. The ratio of the flashover, sparkover, or breakdown voltage of an impulse to the crest value of the power-frequency flashover, sparkover, or breakdown voltage.

Insulation. Material having a high resistance to the flow of electric current, to prevent leakage of current from a conductor.

Insulation Resistance. The ratio of the applied voltage to the total current between two electrodes in contact with a specific insulator.

Insulation System. All of the insulation materials used to insulate a particular electrical or electronic product.

Insulator. A material of such low electrical conductivity that the flow of current through it can usually be neglected.

Interstice. A minute space between one thing and another, especially between things closely set or between the parts of a body.

Ion. An electrified portion of matter of sub-atomic, atomic, or molecular dimensions such as is formed when a molecule of gas loses an electron (when the gas is stressed electrically beyond the critical voltage) or when a neutral atom or group of atoms in a fluid loses or gains one or more electrons.

Ion Exchange Resins. Small granular or bead-like particles containing acidic or basic groups, which will trade ions with salts in solutions.

Ionization. Generally, the dissociation of an atom or molecule into positive or negative ions or electrons. Restrictively, the state of an insulator whereby it facilitates the passage of current due to the presence of charged particles usually induced artificially.

Laminated Plastics: Layers of a synthetic resin-impregnated or coated base material bonded together by means of heat and pressure to form a single piece.

Lamination. The process of preparing a laminate. Also any layer in a laminate.

Line of Force. Used in the description of an electric or magnetic field to represent the force starting from a positive charge and ending on a negative charge.

Mat. A randomly distributed felt of glass fibers used in reinforced plastics.

Moisture Resistance. The ability of a material to resist absorbing moisture from the air or when immersed in water.

Nylon. The generic name for synthetic fiber-forming polyamides.

Open Cell. Foamed or cellular material with cells which are generally interconnected. Closed cells refers to cells which are not interconnected.

Organic. Designating or composed of matter originating in plant or animal life or composed of chemicals of hydrocarbon origin, either natural or synthetic.

Oscillatory Surge. A surge which includes both positive and negative polarity values.

Overpotential. A voltage above the normal operating voltage of a device or circuit.

Overvoltage. See Overpotential.

Partial Discharge: A partial discharge is an electric discharge that only partially bridges the insulation between conductors when the voltage stress exceeds a critical value. These partial discharges may, or may not, occur adjacent to a conductor.

Partial discharge is often referred to as "corona" but the term "corona" is preferably reserved for localized discharges in cases around a conductor, bare or insulated, remote from any other solid insulation.

Partial Discharge Pulse: A partial discharge pulse is a voltage or current pulse which occurs at some designated location in the test circuit as a result of a partial discharge.

Partial Discharge Pulse Charge: The quantity of charge supplied to the test specimen's terminals from the applied voltage source after a partial discharge pulse has occurred. The pulse charge is often referred to as the apparent charge or terminal charge. The pulse charge is related but not necessarily equal to the quantity of charge flowing in the localized discharge.

Partial Discharge Pulse Energy: The partial discharge pulse energy is the energy dissipated during one individual partial discharge.

Partial Discharge Pulse Repetition Rate: The partial discharge pulse repetition rate is the number of partial discharge pulses of specified magnitude per unit time.

Partial Discharge Pulse Voltage: The peak value of the voltage pulse which, if inserted in the test circuit at a terminal of the test specimen, would produce a response in the circuit equivalent to that resulting from a partial discharge pulse within the specimen. The pulse voltage is also referred to as the terminal corona pulse voltage.

Permittivity. Preferred term for dielectric constant.

pH. The measure of the acidity or alkalinity of a substance, neutrality being at pH 7. Acid solutions are under 7, alkaline solutions over 7.

Phenolic Resin. A synthetic resin produced by the condensation of phenol with formaldehyde.

Plastic. High polymeric substances, including both natural and synthetic products, but excluding the rubbers, that are capable of flowing under heat and pressure at one time or another.

Plastic Deformation. Change in dimensions of an object under load that is not recovered when the load is removed.

Plasticizer. Chemical agent added to plastics to make them softer and more flexible.

Polarity. 1) An electrical condition determining the direction in which current tends to flow. 2) The quality of having two opposite charges.

Polyamide. A polymer in which the structural units are linked by amide or thioamide groupings.

Polycarbonate Resins. Polymers derived from the direct reaction between aromatic and aliphatic dihydroxy compounds with phosgene or by the ester exchange reaction with appropriate phosgene derived precursors.

Polyester. A resin formed by the reaction between a dibasic acid and a dihydroxy alcohol.

Polyethylene. A thermoplastic material composed of polymers of ethylene.

Polyisobutylene. The polymerization product of isobutylene, also called butyl rubber

Polymer. A compound formed by polymerization which results in the chemical union of monomers or the continued reaction between lower molecular weight polymers.

Polymerize. To unite chemically two or more monomers or polymers of the same kind to form a molecule with higher molecular weight.

Polymethyl Methacrylate. A transparent thermoplastic composed of polymers of methyl methacrylate.

Polypropylene. A plastic made by the ploymerization of high-purity propylene gas in the presence of an organometallic catalyst at relative low pressures and temperatures.

Polystyrene. A thermoplastic produced by the polymerization of styrene (vinyl benzene).

Polyvinyl Acetate. A thermoplastic material composed of polymers of vinyl acetate.

Polyvinyl Butyral. A thermoplastic material derived from butyraldehyde.

Polyvinyl Chloride (PVC). A thermoplastic material composed of polymers of vinyl chloride.

Polyvinyl Chloride Acetate. A thermoplastic material composed of copolymers of vinyl chloride and vinyl acetate.

Polyvinylidene Chloride. A thermoplastic material composed of polymers of vinylidene chloride (1,1-dichloroethylene).

Potential. Voltage. The work per unit charge required to bring any charge to the point at which the potential exists.

Potting. Similar to encapsulating, except that steps are taken to insure complete penetration of all voids in the object before the resin polymerizes.

Power. The time rate at which work is done; equal to W/t where W is amount of work done in time t. Power will be obtained in watts if W is expressed in joules and t in seconds.

Power Factor. 1) In an alternating current circuit, it is the number of watts indicated by a watt meter, divided by the apparent watts, the latter being the watts as measured by a voltmeter and ammeter. 2) It is the multiplier used with the apparent watts to determine how much of the supplied power is available for use. 3) That quantity by which the apparent watts must be multiplied in order to give the true power. 4) Mathematically, the cosine of the angle of phase difference between current and voltage applied.

Pressure. Force measured per unit area. Absolute pressure is measured with respect to zero pressure. Gauge pressure is measured with respect to atmospheric pressure.

Proton. A positively charged particle believed to be a nuclear constituent of all atoms.

Pulse. A wave which departs from a first nominal state, attains a second nominal state, and ultimately returns to the first nominal state.

Relative Humidity. Ratio of the quantity of water vapor present in the air to the quantity which would saturate it at any given temperature.

Resin. An organic substance of natural or synthetic origin characterized by being polymeric in structure and predominantly amorphous. Most resins, though not all, are of high molecular weight and consist of long chain or network molecular structure. Usually resins are more soluble in their lower molecular weight forms.

Resistance. Property of a conductor that determines the current produced by a given difference of potential. The ohm is the practical unit of resistance.

Resistivity. The ability of a material to resist passage of electrical current either through its bulk or on a surface. The unit of volume resistivity is the ohm-cm, of surface resistivity, the ohm.

Roentgen. The amount of radiation that will produce one electrostatic unit of ions per cubic centimeter volume.

Schering Bridge. An alternating current form of wheatstone bridge, used for comparing capacitances or for measuring the phase angle of a capacitor by comparison with a standard capacitor.

Semiconductor. A material whose resistivity is between that of insulators and conductors. The resistivity is often changed by light, heat, an electric field, or a magnetic field. Current flow is often achieved by transfer of positive holes as well as by movement of electrons. Examples include germanium, lead sulfide, lead telluride, selenium, silicon, and silicon carbide. Used in diodes, photocells, thermistors, and transistors.

Sheet. Any material (conducting, insulating, or magnetic) manufactured in sheet form and cut to suit in processing.

Shelf Life. Length of time under specified conditions that a material retains its usability.

Silicone. Polymeric materials in which the recurring chemical group contains silicon and oxygen atoms as links in the main chain.

Solvent. A liquid substance which dissolves other substances.

Sparkover. A disruptive discharge between electrodes of a measuring gap, such as a sphere gap or oil testing gap.

Specific Gravity. The density (mass per unit volume) of any material divided by that of water at a standard temperature.

Staple Fibers. Fibers of spinnable length manufactured directly or by cutting continuous filaments to short lengths.

Storage Life. The period of time during which a liquid resin or adhesive can be sored and remain suitable for use. Also called Shelf Life.

Surface Creepage Voltage. See Creepage.

Surface Flashover. See Flashover

Surface Leakage. The passage of current over the boundary surfaces of an insulator as distinguished from passage through its volume.

Surface Resistivity. The resistance of a material between two opposite sides of a unit square of its surface. Surface resistivity may vary widely with the conditions of measurement.

Surge. A transient variation in the current and/or potential at a point in the circuit.

Tear Strength. Force required to initiate or continue a tear in a material under specified conditions.

Tensile strength. The pulling stress required to break a given specimen.

Thermal Conductivity. Ability of a material to conduct heat.

Thermal Endurance. The time at a selected temperature for an insulating material or system of materials to deteriorate to some predetermined level of electrical, mechanical, or chemical performance under prescribed conditions of test.

Thermal Expansion (Coefficient of). The fractional change in length (sometimes volume) of a material for a unit change in temperature.

Thermoplastic. A classification of resin that can be readily softened and resoftened by heating.

Tracking. Scintillation of the surface of an insulator, may produce enough heat to leave a degraded track of carbon.

Tracking Resistance. See arc resistance.

Transient. That part of the change in a variable that disappears during transition from one steady-state operating condition to another.

Tubing. Extruded non-supported plastic or elastomer materials.

Urea-Formaldehyde Resin. A synthetic resin formed by the reaction of urea with formaldehyde. An amino resin.

Urethane. See Isocyanate Resins.

Vinyl Resin. A synthetic resin formed by the polymerization of compounds containing the group $CH_2 = CH-$.

Viscosity. A measure of the resistance of a fluid to flow (usually through a specific orifice).

Volt. Unit of electromotive force. It is the difference of potential required to make a current of one ampere flow through a resistance of one ohm.

Voltage. The term most often used in place of electromotive force, potential, potential difference, or voltage drop, to designate electric pressure that exists between two points and is capable of producing a flow of current when a closed circuit is connected between the two points.

Volume Resistivity (Specific Insulation Resistance). The electrical resistance between opposite faces of a 1-cm cube of insulating material, commonly expressed in ohm-centimeters. The recommended test is ASTM D257-61.

Vulcanization. A chemical reaction in which the physical properties of an elastomer are changed by reacting it with sulfur or other cross-linking agents.

Water Absorption. Ratio of the weight of water absorbed by a material to the weight of the dry material.

Wire. A conductor of round, square, or rectangular section, either bare or insulated.

Working Life. The period of time during which a liquid resin or adhesive, after mixing with catalyst, solvent, or other compounding ingredients, remains usable.

Yield Strength. The lowest stress at which a material undergoes plastic deformation. Below this stress, the material is elastic; above it, viscous.

4. BACKGROUND

There are three important procedures for high density, high voltage, high power airborne equipment dielectric design and packaging. These procedures are:

- The design should make use of high quality materials designed within the electrical and mechanical stress limits of the materials.
- Circuit and component materials should be modeled and proven adequate for the design by electrical and mechanical testing. These tests should be used to determine the electrical, mechanical, and chemical characteristics and compatibility of parts and equipment and not as a failure tool after insulation failure.
- All parts, components, and assemblies should be fabricated in clean rooms by personnel knowledgeable in clean room procedures.

4.1 Program Plan and Requirements. High-voltage high-power equipment in future airplanes will operate in the 3,000 to 250,000 volt region, which is considerably higher than previously experienced in aircraft equipment. The consequences of a high-voltage breakdown on a mission need not be elaborated on here. The important point is that every high-voltage insulation failure in the past could have been prevented by thoroughly specified requirements, carefully conducted design, and adequate and properly planned testing to demonstrate that all requirements are met. Particularly troublesome are interfaces where equipment and responsibilities meet.

High-voltage circuit and component insulation must be analyzed by specialists, particularly when temperature cycling, high-density packaging and high-power equipment are involved. For example, consider components which are subjected to environmental and electrical testing prior to flight. During testing, the components may be electrically overstressed, connected and reconnected, the cables flexed and vibrated, and occasionally some parts may be exposed to hostile fumes and temperatures. These mechanical, chemical, and electrical stresses degrade electrical insulation. The specialist must show by analyses, tests, or test similarities, that stressing produces insignificant materials degradation and has little impact on the life of the insulation. Improperly tested components must be further analyzed and/or retested to show flightworthiness.

It is essential that the (1) insulation materials, (2) test requirements, and (3) specifications be developed prior to hardware fabrication.

4.2 Requirements Specification. Each item of equipment in an airplane must (1) perform its function, and (2) not interfere with other equipment or systems on the airplane or a companion airplane, when two or more airplanes are involved. For a mission to be successful from both standpoints, the equipment must be correctly specified and must meet specified requirements.

An important initial part of a high-voltage,high-power design is the specification of requirements which defines the mission temperature-pressure profile, operating time, voltages, types of enclosures, and the electrical characteristics of nearby materials and equipment. Included must be the testing, storage, and all pertinent military, NASA, and public standards and specifications.

Occasionally, a specification or standard has inadequate electrical or environmental test requirements. Then deviations, deletions, and/or additions must be written. For example, the tests in the military specification for transformers [1], MIL-T-27, are inadequate to ferret out pinholes and voids in the electrical insulation of low voltage transformers and inductors.

4.3 Planning a High-Voltage Program. A program plan is a necessary element that bridges the requirements specification to the specifications that define the system, equipment and circuits as shown in Figure 1. This program plan should include pre-flight testing, storage, and airplane constraints.

A good high-voltage program plan includes a requirements plan and a design-and-test-plan. The requirements plan (Figure 2) includes evaluation of historical data applicable to the equipment and the airplane, operational constraints, and the test and test equipment requirements. Historical data for aerospace equipment operating at voltages up to 10 kilovolts is abundant.[2] Likewise, materials, designs, and manufacturing techniques for this voltage region are

1. "Transformers and Inductors (Audio, Power, and High-Power Pulse) General Specification For", MIL-T-27D, April, 1974
2. J. E. Sutton and J.E. Stern, "Spacecraft High-Voltage Power Supply Construction," NASA TN D7948, Goddard Space Flight Center, Greenbelt Md., April, 1975

readily available. For voltages over 10 kilovolts information is scarce, and research and development tailored to the constraints and requirements unique to the airplane and equipment aboard the airplane is often needed.

High-voltage testing becomes hard to define for several reasons. First, the supplier of electronic components may lack some test equipment or test experience within his design organization, necessitating compromises in the hierarchy of testing; second, there are several levels of testing to be performed with difficult-to-evaluate options on when to perform what tests; third, test equipment sensitivity is affected by the equipment being tested and the connection thereto. Some equipment and experiments can actually be designed to test themselves. All these elements must be defined in the requirements plan by the equipment designer, and his customer, before preliminary design review.

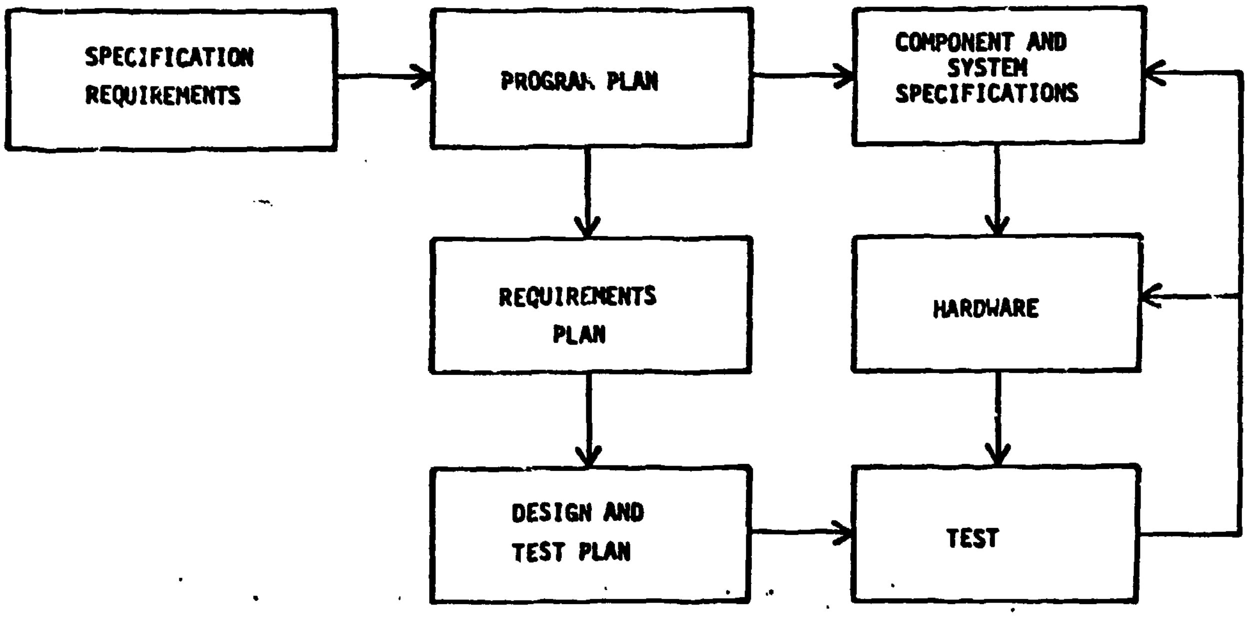


FIGURE 1. HIGH-VOLTAGE, HIGH-POWER SYSTEM DEVELOPMENT PLAN

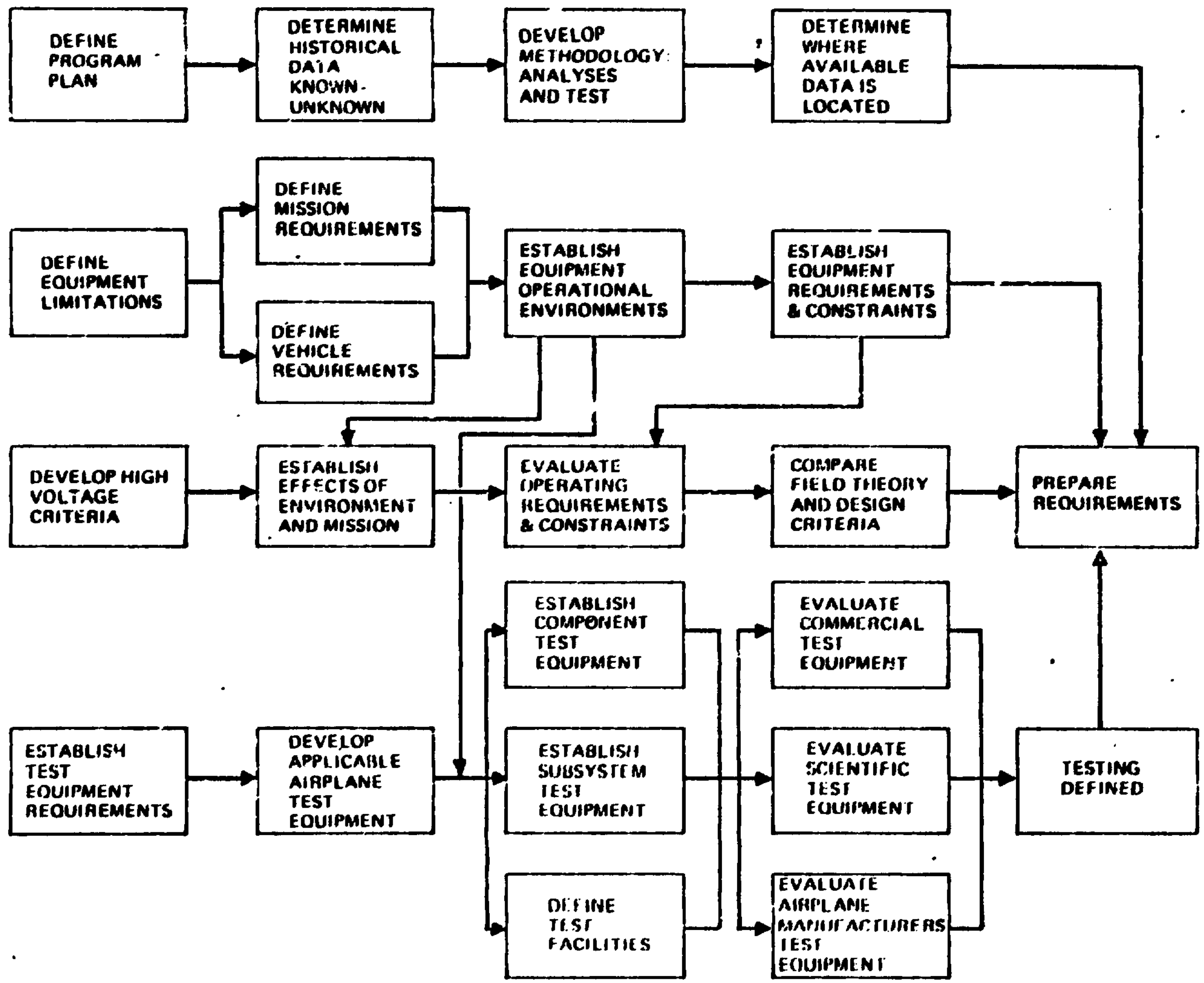


FIGURE 2. REQUIREMENTS PLAN

4.4 Design-and-Test Plan. A design-and-test plan should be developed for each high-voltage component aboard the airplane. It should contain the constraints and requirements that affect the design; for example, pressure, temperature, and outgassing products other than air.

Testing should be time sequenced with other phases of the high-voltage system development such as design, materials selection and application, and packaging, to avoid delays and costly overruns from improper application of a specific material. The design and test plan, shown in Figure 3, requires that the insulating and conducting materials be selected and tested early in the program to establish their adequacy and life-stress capability.

Dense parts packaging, where mechanically stressed insulation must withstand wide temperature variations, are particularly important to watch. Some insulations crack when subjected to temperatures lower than $-20^{\circ}C$, and with high electric fields between parts, cracked insulation is a precursor to partial discharges and ultimate failures.[3]

3. W.G. Dunbar, "High Voltage Connections for Flight Vehicles," Proc. 9th Intersociety Energy Conversion Engineering Conference, San Francisco, California, August 1974, pp 251-258

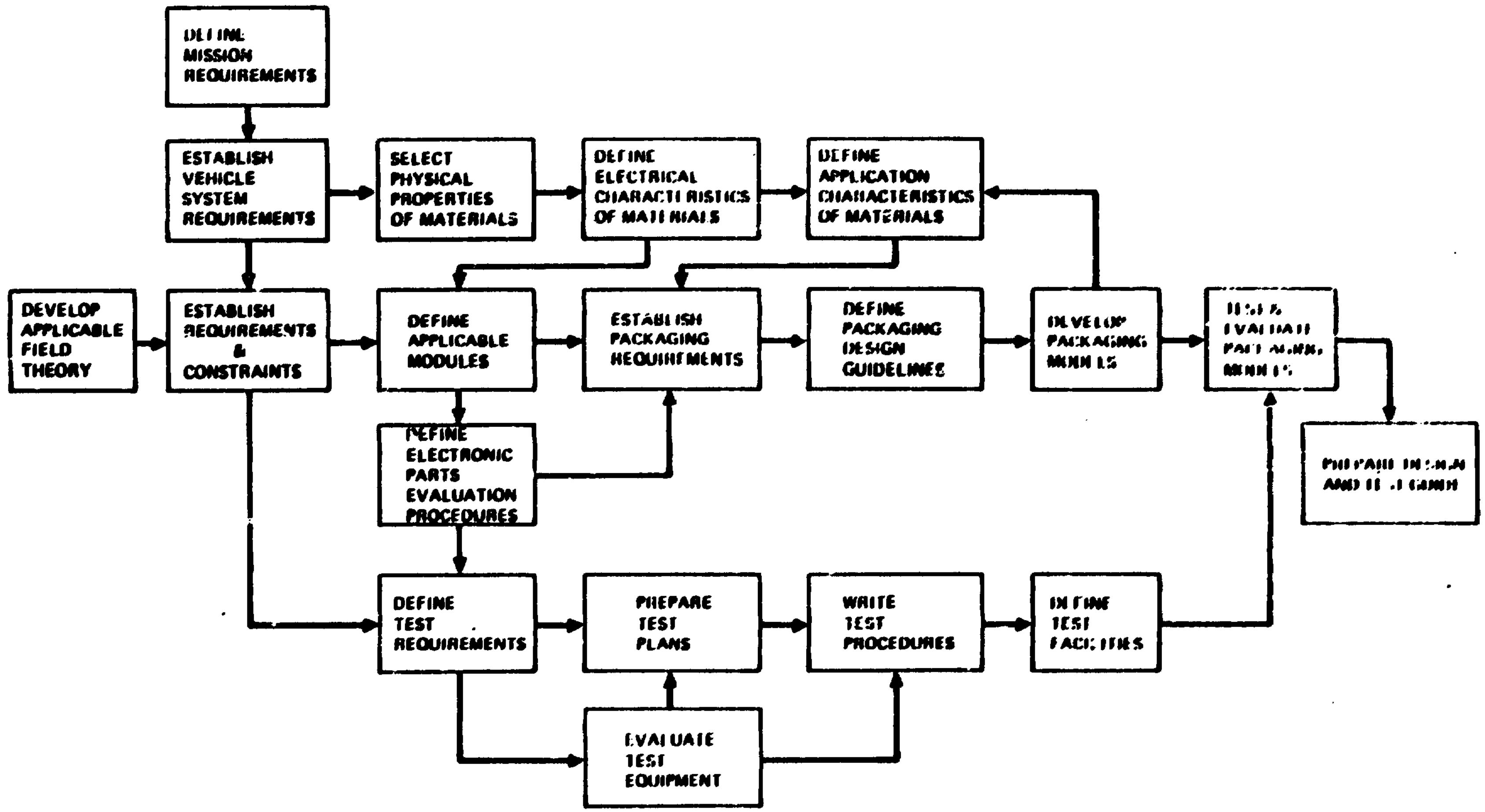


FIGURE 3. DESIGN AND TEST PLAN

5. FUNDAMENTALS OF INSULATIONS

Changes in insulation properties resulting from electric field and temperature variations, mechnical stress, and surface contact with electrodes are fundamental contributors to voltage breakdown. The designer dealing with these changes in insulation properties needs to understand certain fundamental characteristics of insulation behavior. Basic theory of gas, liquid, and solid insulation is provided to an appropriate depth in this section. Excellent texts on dielectric phenomena are listed as References 4 through 8.

5.1 Gases. Much has been written about the theory of gas breakdown, and data obtained under a variety of conditions has been published (References 9 through 17). A brief review and discussion of this theory follows.

4) W.R. Smythe, Static and Dynamic Electricity, McGraw-Hill Book Co., New York, N.Y., 1968.

5) J.D. Stratton, Electromagnetic Theory, McGraw-Hill Book Co., New York, N.Y., 1941.

6) E. Weber, Electromagnetic Fields, John Wiley and Sons, Inc., New York, N.Y., 1950.

7) A.R. Von Hippel, Dielectric Materials and Application, John Wiley and Sons, Inc., 1954.

8) E.W. Greenfield, Introduction to Dielectric Theory and Measurements, College of Engineering, Washington State University, Pullman, Washington, 1972.

9) J.M. Meek and J.D. Craggs, Electrical Breakdown of Gases, John Wiley and Sons, New York, N.Y., 1978.

10) L.B. Loeb, Electrical Coronas, University of California Press, Berkeley, California, 1965.

11) J.D. Cobine, Gaseous Conductors, New York, New York, Dover, 1958.

12) A. Von Engel, Ionized Gases, London, Oxford University Press, 1955.

J.S. Townsend proposed his theory of gas breakdown in the early 1900's.[18] Much has since been added, but his original work is still the basis for most studies.

When an electrical potential is impressed across a gas, a small pre-breakdown current can be measured because free electrons drift from the cathode or negative electrode to the anode or positive electrode. At low potential the apparent circuit resistance is high because the electrons collide with neutral gas molecules in the gap. Some electrons find their way to the anode due to the elasticity of the collisions. As the potential is raised, electron velocity is increased, and some electrons gain sufficient energy to ionize the gas by collision, separating molecules into new free electrons and positive-ion pairs. The new free electrons are accelerated and ionize more molecules generating electrons at an expoential rate with respect to applied voltage. This process, called avalanche breakdown of the gas, is shown in Figure 4, where the pre-breakdown current is labeled "recombination." Recombination is where the electrons released from a cathode by background radiation, for example, a cosmic ray, tend to return to the cathode by back diffusion and because of the space charge field. The region labeled "secondary ionization" is where the initiating electrons (N_0) cause α ionizations per unit distance traveled through the field. The number

13) F.L. Jones, Ionization and Breakdown of Gases, John Wiley and Sons, New York, New York, 1957.

14) F. Llewellyn-Jones, The Glow Discharge, Methuer and Co., Ltd., London, England, 1966.

15) L.B. Loeb, Basic Processes of Gaseous Electronics, 2nd Edition, University of California Press, Berkeley, California, 1960.

16) F.M. Penning, Electrical Breakdown of Gases, MacMillan Company, New York, N.Y., 1957.

17) G.P. Thomson, Conduction of Electricity Through Gases, Cambridge University Press, Vol. 2, 3rd Edition, London, England, 1928.

18) J.S. Townsend, Electricity in Gases, Oxford University Press, London, England, 1914.

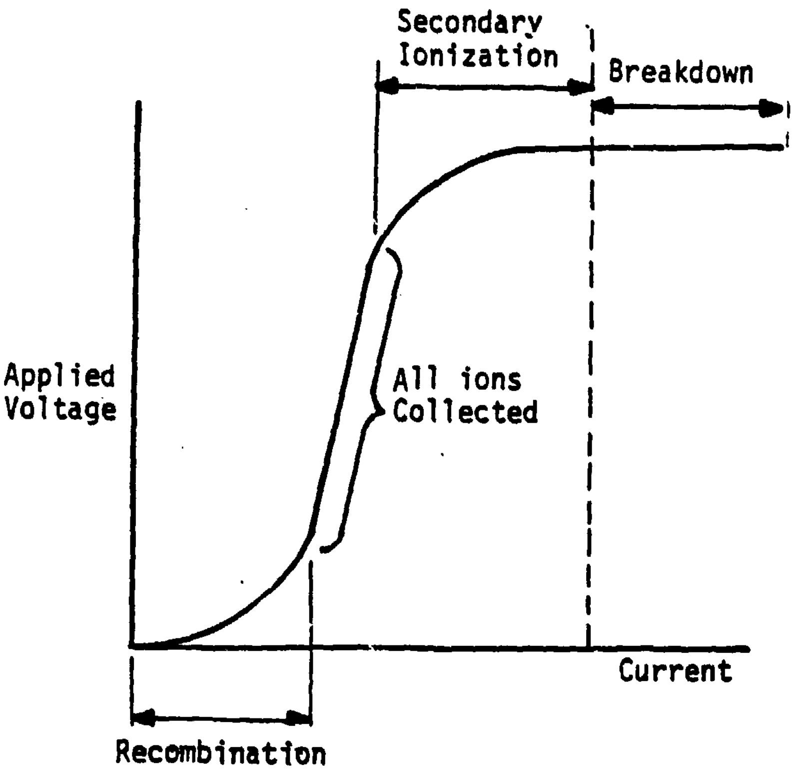


FIGURE 4. VOLTAGE-CURRENT CHARACTERISTIC FOR A GAS IN A UNIFORM ELECTRIC FIELD

of electrons (N) reaching the anode at a distance d is then

$$N = N_o e^{\alpha d} \tag{3.1}$$

Further increase in applied voltage puts us in the breakdown region where additional electrons are released principally by positive ion bombardment of the cathode. This condition is described by the sequence of events shown in Figure 5.[19] Townsend's criterion for breakdown is

$$\gamma(e^{\alpha\delta} - 1) = 1 \tag{3.2}$$

19) W.H. Krebs and A.C. Reed, "Low Pressure Electrical Discharge Studies", STL/TR-59-0000-09931, Air Force Contract 04(647)-309, December 1959.

Where γ is the secondary Townsend coefficient and δ is the path in the direction of the field in centimeters.

Three mechanisms for releasing electrons from a cold cathode are:

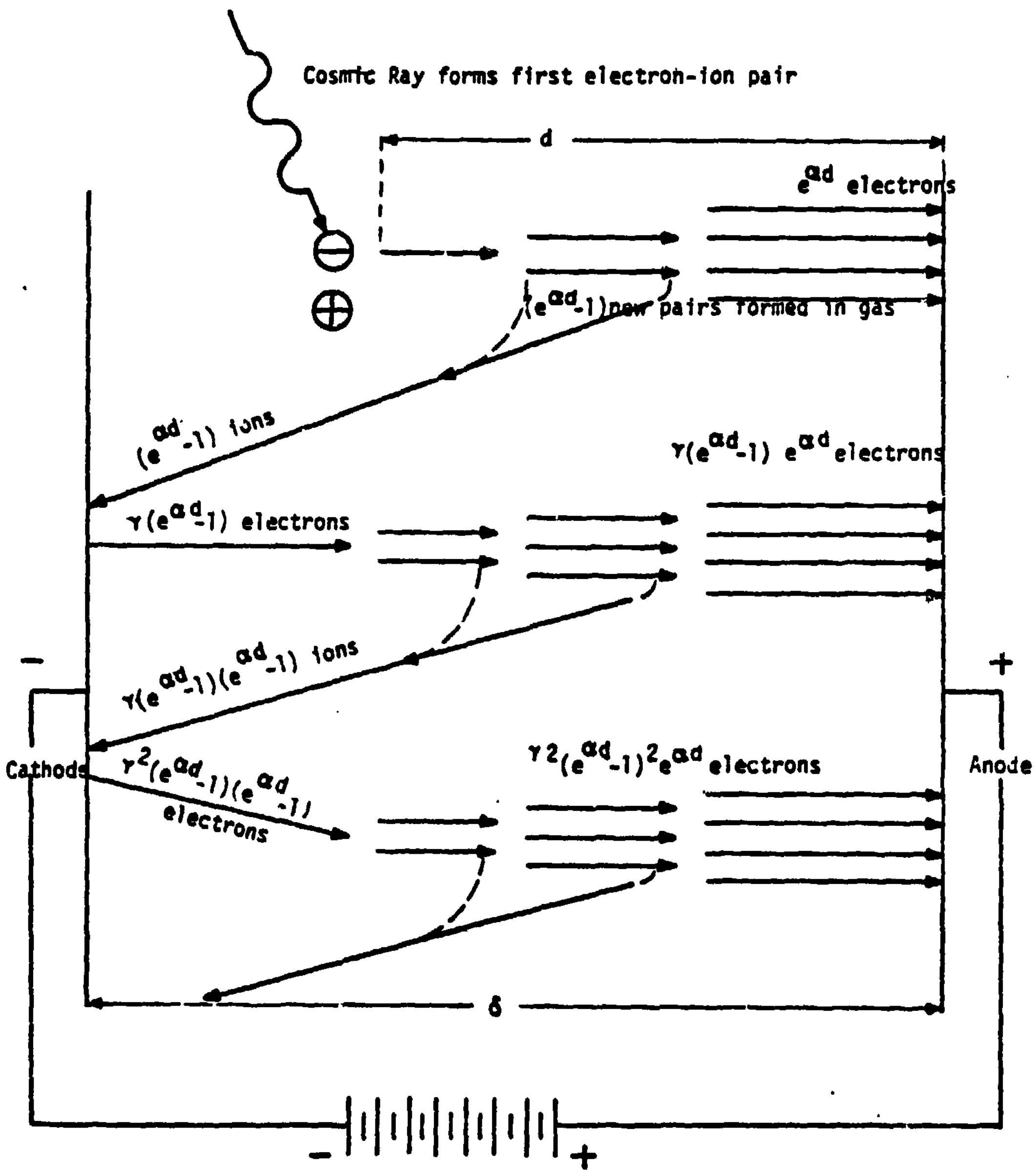


FIGURE 5. DERIVATION OF TOWNSEND'S BREAKDOWN CRITERION

- o Arriving positive ions strike the cathode
- o Light radiation falls on the cathode
- o Light results from excitation of molecules by collision with electrons which do not have enough energy to produce ionization.
- o A metastable molecule, which evolved from an electron-molecule collision, diffuses back to the cathode (Figure 5).

5.1.1 Corona. Loeb [10] describes the phenomena of corona in the following manner. "Except at relatively low pressures, the luminous manifestations at the highly stressed electrode near the threshold for the low currents take on various characteristic shapes, such as flows, multiple spots, haloes, coronas, brushes, streamers, etc. In consequence, these luminous manifestations gave to the phenomena the general name, coronas. It comes from the French word couronne, literally crown, which typifies one of the various forms observed. This expression, corona, will be used to describe the general class of luminous phenomena appearing associated with the current jump to some microamperes at the highly stressed electrode preceding the ultimate spark breakdown of the gap. Where observed, the sudden current jump, usually just preceding the initial appearance of the corona and the associated value of the potential, will be designated as the corona threshold. The threshold for the appearance of a corona form may be further classified in terms of the characteristic phenomenon or mechanisms associated with it, such as the burst pulse threshold, the streamer threshold, the Trichel pulse threshold, or the glow discharge threshold. The current at many such thresholds is pulsating or intermittent in nature. Depending on the geometry and the spectroscopic nature of the gas, the intermittent or pulsed thresholds may not show luminosity in all cases. If the potential is raised on the order of some hundreds of volts above threshold, the frequencies of the intermittent pulses become so great that they merge to a nearly steady but slightly fluctuating current. Transition from intermittent to the steady state is sometimes sharp and is described as the onset of steady corona. Above the onset of steady corona there will be a limited region, in which current increases nearly proportional to potential increase. This is called the Ohm's law regime. After this the current increases more rapidly than the potential, that is, parabolically, eventually leading to a complete breakdown, which will be so designated."

Corona is reserved for discharges in gases around a conductor, bare or insulated, remote from any other conductor. Corona should not be confused with partial

discharges, ionization, or breakdown. Partial discharges are electric discharges which only partially bridge the insulation between conductors. These discharges may, or may not, occur adjacent to a conductor. Ionization describes any process producing positive or negative ions, or electrons, from neutral atoms or molecules and should not be used to denote partial discharges.

5 1.2 Pashen Law. The breakdown voltage of a uniform-field gap in a gas can be plotted to relate the voltage to the product of the gas pressure times the gap length. This is known as Paschen's law curve. [10] The law may be written in the general form:

$$V = f(\rho d)$$

where ρ is the gas density, and d is the distance between parallel plates. In words, Paschen's law states: "As gas density is increased from standard temperature and pressure, the voltage breakdown is increased because at higher densities the molecules are packed closer, and a higher electric field is required to accelerate the electrons to ionizing energy within the mean free path. The voltage breakdown decreases as gas density is decreased from standard pressure and temperature because the longer mean free path permits the electrons to gain more energy prior to collision. As density is further decreased, the voltage breakdown decreases until a minimum is reached".

As density is further reduced to values less than the Paschen law minimum, the voltage breakdown rises steeply because the spacing between gas molecules becomes so large that although every electron collision produces ionization, it is hard to achieve enough ionizations to sustain the chain reaction. Finally, the pressure becomes so low that the average electron travels from one electrode to the other without colliding with a molecule. This is why the minimum breakdown voltage varies with gas density and spacing. Examples of Paschen-law curves for several gases are shown in Figure 6.

The pressure corresponding to minimum breakdown depends on the spacing of the electrodes; for a 1-centimeter spacing at room temperature this pressure occurs at about 100 Pascals. One Pascal is equal to one newton per square meter or 7.5×10^{-3} torr. A representative minimum for air is 326 volts d.c. For a contact spacing of one centimeter at standard atmospheric conditions the breakdown voltage of air is 31 kilovolts.

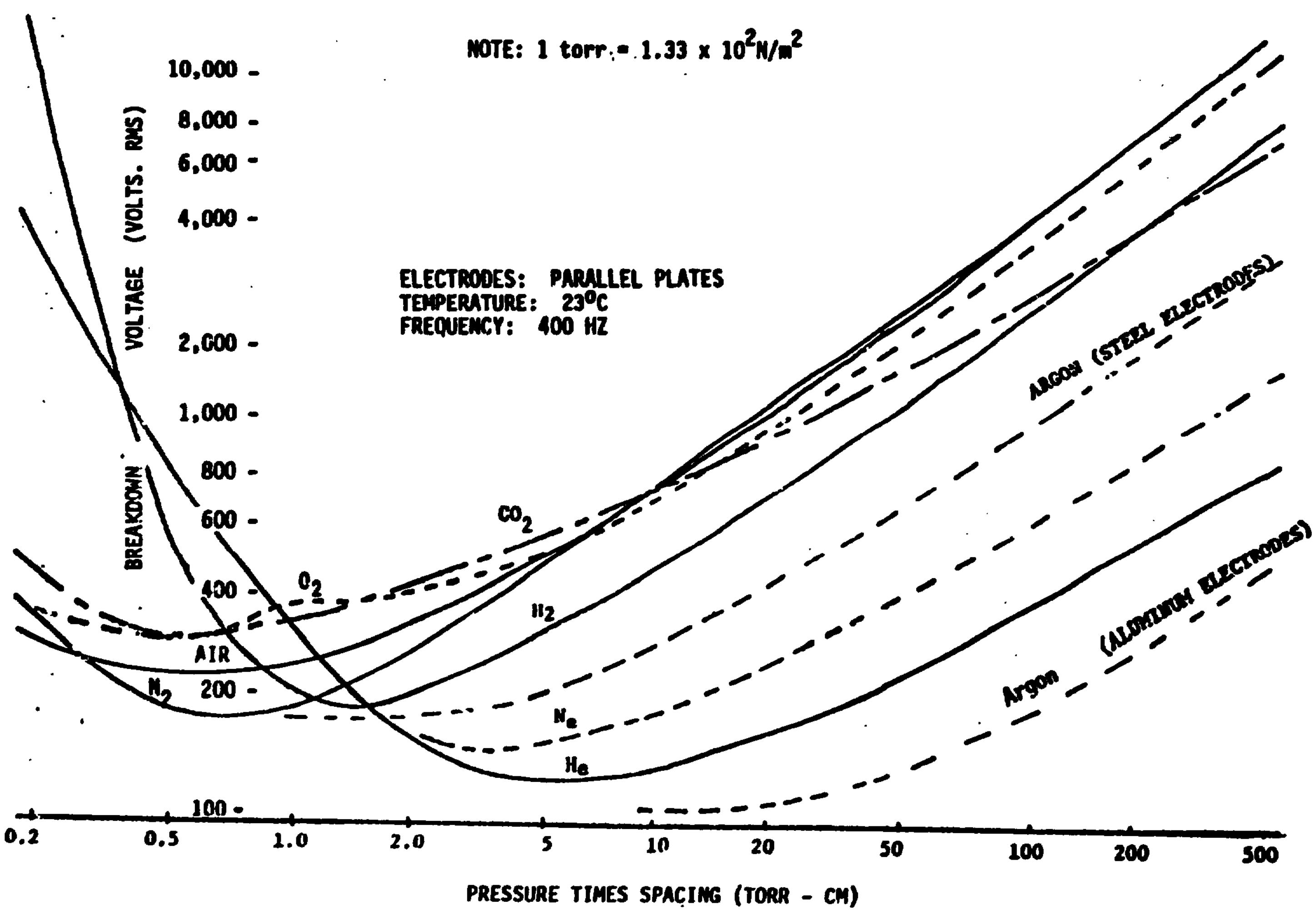


FIGURE 6. VOLTAGE BREAKDOWN OF PURE GASES AS A FUNCTION OF PRESSURE TIMES SPACING

Voltage breakdown, under normal conditions, has no sharply defined starting voltage because its initiation depends on an external source of ionization. There is generally a time delay between the application of voltage and breakdown. This time delay varies statistically and is a function of the difference between the applied voltage and the "critical voltage". Ultra-violet and higher-energy radiation will reduce the time delay considerably.

Paschen-law curves for non-uniform fields become difficult to predict because the effective gap length is not easily defined.

5.1.3 Penning Effect. Penning [16] discovered that if a trace (much less than one percent) of a gas such as argon was mixed into a gas such as neon, a large reduction in the breakdown voltage occurred. This is caused by the metastable neon atoms ionizing the argon atoms. Gas mixtures having this characteristic are helium-argon, neon-argon mixtures, helium-mercury, and argon-iodine. Airplane compartments containing helium must be kept free of argon to prevent the possibility of low voltage breakdown.

5.1.4 Breakdown of Gases. Electrical and electronic equipment must be designed to operate at the maximum specified altitude and temperature. Most low voltage equipment (voltages to 300 volts peak) can be designed to meet this requirement by coating the circuit boards. High voltage circuit (over 300 volts peak) designs must consider the probability of gas breakdown between parts on the circuit boards and between circuit boards or a circuit board and ground.

The potentials required for voltage breakdowns in gases at the minimum pressure-spacing condition (Paschen-law minimum) and between parallel plates spaced one centimeter apart at pressure, are listed in Table 1. Of these gases, conditioned air is used whenever possible. It is not recommended to use other gases at low pressure because they may give off toxic fumes or form corrosive decomposition products during the airing process. Therefore many high voltage modules are either plotted or pressurized.

TABLE 1
BREAKDOWN VOLTAGE BETWEEN BARE ELECTRODES SPACED ONE CENTIMETER

Gas	Minimum at Critical Pressure Spacing		Breakdown Voltage at 1 Atmosphere	
	Volts (a.c. rms)	Volts (d.c.)	Kilovolts (a.c.)	Kilovolts (d.c.)
Air	223-230	315	23	33
Ammonia	—	—	18.5	26
Argon	196	280	3.4	4.8
Carbon Dioxide	305	430	24	28
Freon 14	340	480	22.8	32
Freon 114	295	420	64	90
Freon 115	305	430	64	90
Freon 116	355	500	—	—
Freon C 138	320	450	—	—
Helium	132	189	1.3	1.63
Hydrogen	205	292	12	17
Nitrogen	187	265	22.8	32
Oxygen	310	440	—	—
Sulfur Hexafluoride	365	520	63	89

Pressuring gases include all the gases listed in table 1 and shown on Figure 6. Some gases have very low breakdown characteristics and should not be considered. Helium is an example. The fluorocarbons are the preferred gases. Of these gases sulfer hexafluoride is generally the preferred gas because it is stable, electronegative, and easily obtained. Sulfer hexafluoride (SF_6) gas is used in compact switching equipment, substations, cables, and other commercial high voltage equipment. It should be the first gas considered for high-voltage airplane equipment when component density and other high voltage criteria suggest that a gas-pressurized installation is best.

Air and nitrogen gases are also used for pressurized circuits. These gases have similar breakdown characteristics, are readily available, and require little special handling. First, the characteristics of air are discussed for non-uniform fields.

Non-Uniform Fields. The utilization factor is defined as the ratio of the average to the maximum gradient across a gap. The minimum sparkover for a non-uniform field, V_s, is given by the relationship

$$V_s = gE_s \tag{3.4}$$

Where E_s is the sparkover gradient and g is the gap dimension. Where η is a function of the electrode geometry and material, and can be calculated for practical configuration such as shown in Figure 7. An example of a breakdown-voltage curve is shown in Figure 8. Equations for the breakdown of air between the electrodes in Figure 7 are given in Table 2. The equations in Table 2 are empirical based upon experimental data.

5.1.5 Electronegative Gases. Elements having outer rings deficient of one or two electrons form molecules and compounds which are able to capture free electrons, forming heavy and relatively immobile negative ions. The negative charge of such an ion equals the number of free electrons captured. Gases forming such ions, called electronegative gases, have high dielectric strength because the heavy ions arrest the formation of electrical discharges normally initiated by mobile electrons. The number of attaching collisions made by one electron drifting one centimeter in a field is the attachment coefficient n. The criterion for breakdown in an electronegative gas is:

$$\frac{\gamma a}{\alpha - n}\left[e^{(\alpha - n)} - 1\right] = 1 \tag{3.3}$$

Gases with oxygen and halogen atoms are electronegative and hence good insulators, in contrast to hydrocarbon and noble gases. Some electronegative gases are sulfur hexafluoride (SF_6) dichlorodifluoromethane (C $C2_2F_2$), perfluoropropane (C_3F_8), perfluorobutane (C_4F_{10}), hexafluoroethene (C_2F_6), chloropentafluoroethene (C_2ClF_5), dichlorotetrafluoroethane ($C_2Cl_2F_4$), tetrafluoromethane (CF_4), and SF_6-nitrogen or fluorocarbon mixtures.

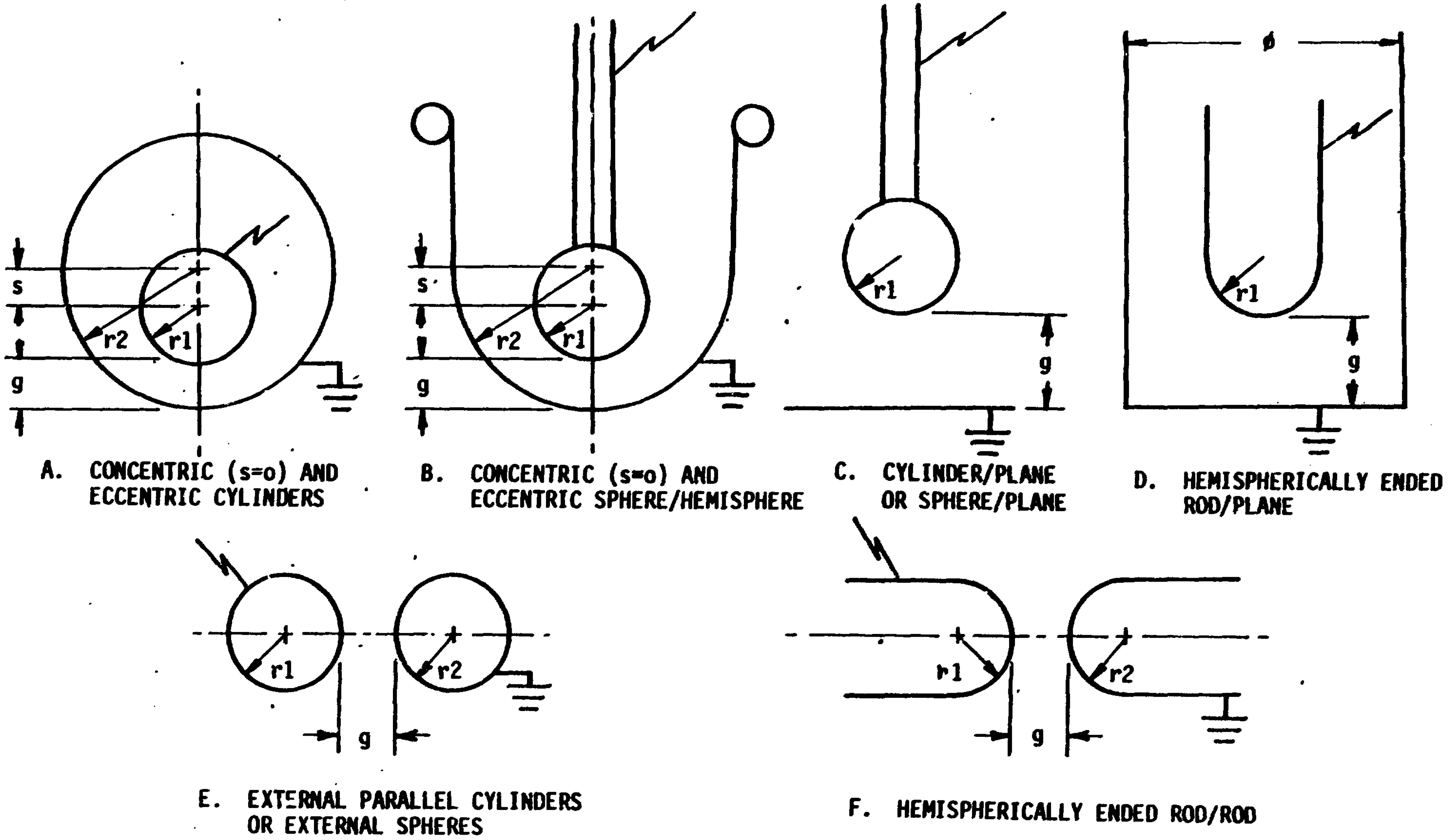


FIGURE 7 ELECTRODE GEOMETRIES

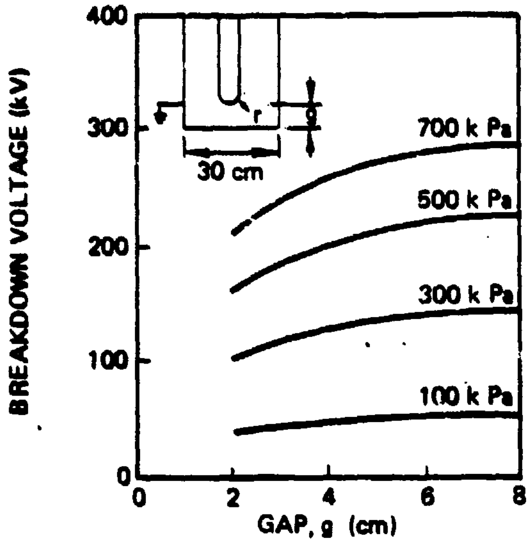


FIGURE 8 SPARKOVER VOLTAGE IN AIR FOR r = 1.27 cm RADIUS ELECTRODES

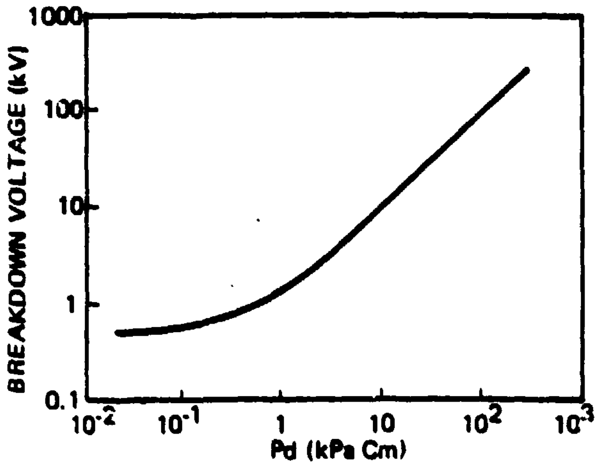


FIGURE 9A PASCHEN CURVE FOR SF_6 FOR DIRECT APPLIED VOLTAGES

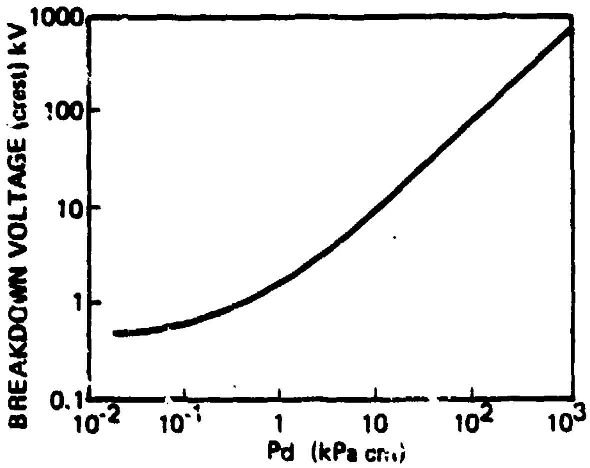


FIGURE 9B PASCHEN CURVE FOR SF_6 FOR ALTERNATING (50 OR 60 Hz) APPLIED VOLTAGES

TABLE 2

SPARKOVER GRADIENTS IN AIR

Pressure $N/m^2 \times 10^5$	Electrode Geometry (See Fig. 6)	Range of Dimension mm (See Fig. 6)	Voltage Waveform		Equation E_s in kV/mm	Typical Error Range
1.013	concentric cylinders	$0.59 \le r_1 \le 15.9$ r_2 not specified	50 Hz	(1)	$E_s = 3.1(1+0.975/\sqrt{r_1})$	+ 1.4 - 5.4
1.013	concentric cylinders	$3.96 \le r_1 \le 38.1$ $r_2 = 290.5$	50 Hz	(2)	$E_s = 2.2(1+1.71/\sqrt[3]{r_1})$	
1.013	concentric cylinders	not specified	50 Hz	(3)	$E_s = 2.4\ 1+1.49/(r_1)^{0.4}$	
1.013	concentric cylinders		50 Hz	(4)	$E_s^2 - 4.56E_s \ln(4.39E_s) = 5.2 + 0.24/r_1$	
1.013	concentric cylinders	$10 \le r_1 \le 150$ r_2 not specified	50 Hz	(5)	$E_s = 2.721(1+1.55/\sqrt{r_1})$	$\pm$ 3.5
	eccentric cylinders	$12.7 \le r_1 \le 38.1$ $r_2 = 63.5$ $5 \le S \le (r_2 - r_1)$				$\pm$ 3
1 < P < 5	concentric cylinders	$25.4 \le r_1 \le 80$ r_2 not specified	50 Hz	(6)	$E_s = 2.12(1+3.55\sqrt{pr\ 1\times10^{-5}}$	$\pm$ 4
1.013	concentric sphere/ hemisphere	$5 \le r_1 \le 125$ $72.5 \le r_2 \le 203.2$	50 Hz	(7)	$E_s = 2.4(1+3.16/\sqrt{r_1})$	$\pm$ 4
	eccentric sphere/ hemisphere	$8.75 \le r_1 \le 38.1$ $r_2 = 72.5$ $0 \le S \le 0.9(r_2 - r_1)$				
1.013	parallel external cylinders	$r_1 = r_2$ $0.098 \le r_1 \le 4.64$	50 Hz	(8)	$E_s = 2.98(1+0.95/\sqrt{r_1})$	+ 3.7 - 6.2

These gases are chemically inert and have good thermal stability, but can decompose chemically when exposed to partial discharges or arcs. The products of decomposition are often toxic and corrosive. In addition, a small quantity of water decomposes the SF_6 to form hydrofluoric acid when in the presence of a partial discharge or arc. Once formed, the hydrofluoric acid etches into crevices and requires special cleaning of all parts within the pressurized module. Examples for the breakdown-voltage equations for SF_6, using the non-uniform configurations of Figure 7 are shown in Table 3. The equations are based on measurements made mainly using coaxial-cylinder gaps.

5.1.6 Sulfur Hexafluoride (SF_6). The power frequency uniform field voltage breakdown characteristic of SF_6 can be altered from its initial state by mixing with other gases, changing the field configuration, changing from power frequency to high frequency or pulses, selecting electrode materials other than steel, and by coating the electrodes. DC and ac Paschen curves for SF_6 in uniform fields are shown in Figure 9 and Table 4 (reference 20). The minimum of the Paschen curve occurs at 35 Pa-cm and is near 500 volts dc. Deviations exist for values above 300 kPa-cm and below 10 Pa-cm for small spacings and higher pressures. A comparison of the voltage breakdown of SF_6, N_2, and other gases is shown in Figure 10.

Mixtures. SF_6 gas has excellent heat transfer and dielectric properties, making it an excellent pressurizing gas. Mixing SF_6 with other gases will improve some characteristics with little change to the direct voltage uniform field dielectric strength as shown for mixtures in air, carbon dioxide and nitrogen in Figure 11 (reference 21).

20. N. H. Malik and A. H. Qureshi, "Breakdown Mechanisms in Sulfur-Hexafluoride", IEEE, Trans on Elec. Insulation, Vol. EI-13, No. 3, June 1978, pp. 135-145.

TABLE 3

PUBLISHED EQUATIONS FOR SPARKOVER GRADIENTS E_S, IN SF_6

Pressure $p \times 10^5 N/m^2$	Electrode Geometry (see Fig. 6)	Range of Dimensions mm (see Fig. 6)	Voltage Waveform	Equation E kV/mm See note
$1 < p < 4$	concentric cylinders	$2.5 \le r_1 \le 25$ $30 \le r_2 \le 140$	50 Hz	(1) $E_S = \frac{5.3(1+0.459p)}{1+(2.82-2.29/p)/\sqrt{r_1}}$
$1 < p < 4$	concentric cylinders	$19 \le r_1 \le 100$ $100 \le r_2 \le 270$	50 Hz	(2) $E_S = 4.28p+3.8$
			negative impulse	(3) $E_S = 6.43p+3.0$
			negative impulse	(4) $E_S = 4.59p+3.5$
	sphere/sphere	$r_1 = r_2 = 125$ $20 \le g \le 80$	50 Hz	(5) $E_S = 6.12p+2.3$
			negative impulse	(6) $E_S = 6.74p+2.6$
$1 < p < 4$	concentric cylinders	not specified but expected to be $19 \le r_1 \le 100$ $100 \le r_2 \le 270$	positive impulse	(7) $E_S = 8/12p+1.0$
$1 < p < 6$	sphere/plane	$10 \le r_1 \le 25$ $20 \le g \le 500$	positive impulse	(8) $E_S = 8.78p$+correction factor
$1 < p < 5$	sphere/sphere	$r_1 = r_2 = 75$ $0 \le g \le 120$	50 Hz	(9) $E_S = \frac{8.78p}{(1+0.557/\sqrt{pr_1})}$
	hemispherically ended rod/rod	$r_1 = r_2$ $5 \le r_1 \le 15$ $0 \le g \le 200$		

TABLE 4

AC BREAKDOWN VOLTAGES FOR SF_6

IN UNIFORM FIELD GAPS

TEMPERATURE = 25°C

pd	50 Hz CREST BREAKDOWN VOLTAGE kV													
	DISTANCE mm													
kPa cm	1	2	3	5	8	10	15	20	25	30	40	50	60	
10	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	
40	26.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	35.5	
80	42.5	55.5	64.5	70.5	70.5	70.5	70.5	70.5	70.5	70.5	70.5	70.5	70.5	
100	50.0	60.0	74	89	89	89	89	89	89	89	89	89	89	
200	98.0	103	120	150	168	170	170	170	170	170	170	170	170	
300		144	155	190	217	240	263	263	263	263	263	263	263	
400		177	185	220	250	275	303	310	310	310	310	310	310	
500			216	248	275	305	356	385	385	385	385	385	385	
600			250	278	305	340	395	440	455	455	455	455	455	
800				335	370	390	450	500	535	580	580	580	580	
1000				395	420	450	505	555	595	635	730	730	730	
1200					485	505	562	610	650	685	750	805	870	
1400					535	565	620	668	715	748	808	865	(920)	**
1600					585	618	678	725	768	(805)*	(865)	(920)	(970)	
1800						680	733	(785)*	(825)	(862)	(925)	(975)	(1025)	
2000						735	(790)*	(840)	(880)	(920)	(975)	(1025)	(1075)	

*Numbers in brackets () are extrapolated which may give doubtful accuracy.

**Values below the break line lie outside the range for which the Paschen law holds true.

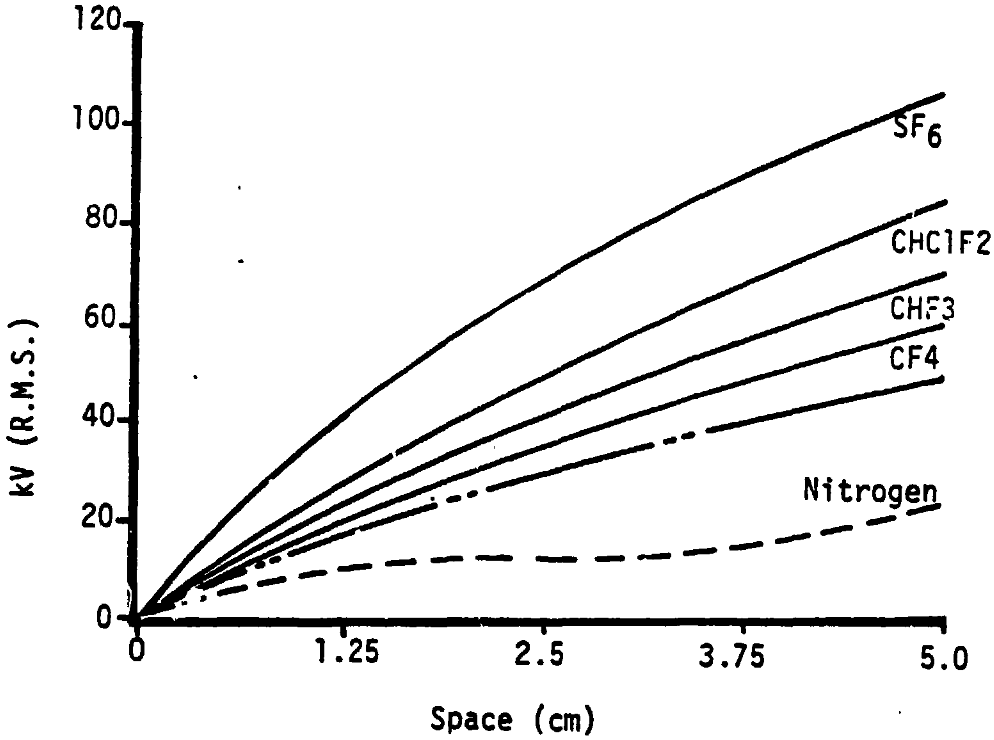


FIGURE 10 BREAKDOWN VOLTAGE CURVES OF GASES BETWEEN A HEMISPHERICALLY-ENDED ROD, OF 0.1 IN. DIAMETER, AND A SPHERE OF 1.0 IN. DIAMETER. THE GAS PRESSURE IS 1 ATM.

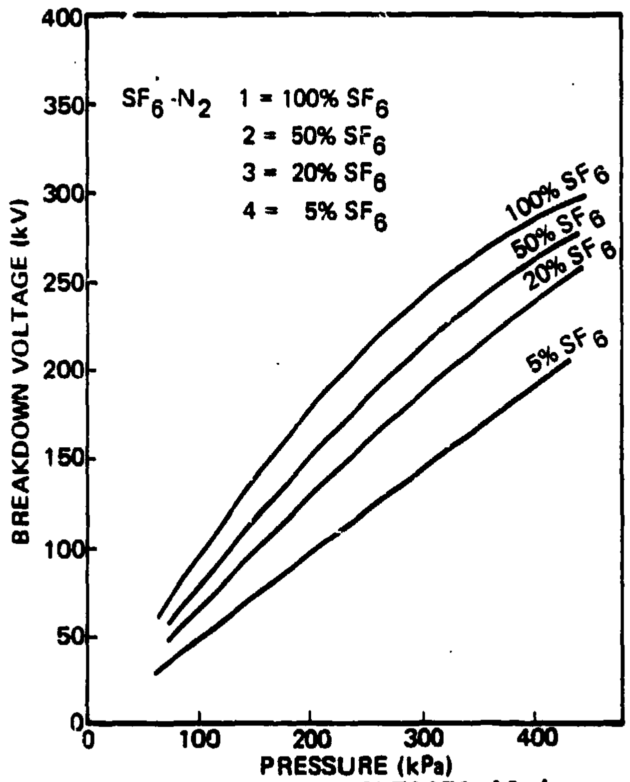


FIGURE 11A BREAKDOWN VOLTAGES AS A FUNCTION OF GAS PRESSURE FOR SF_6-N_2 MIXTURES

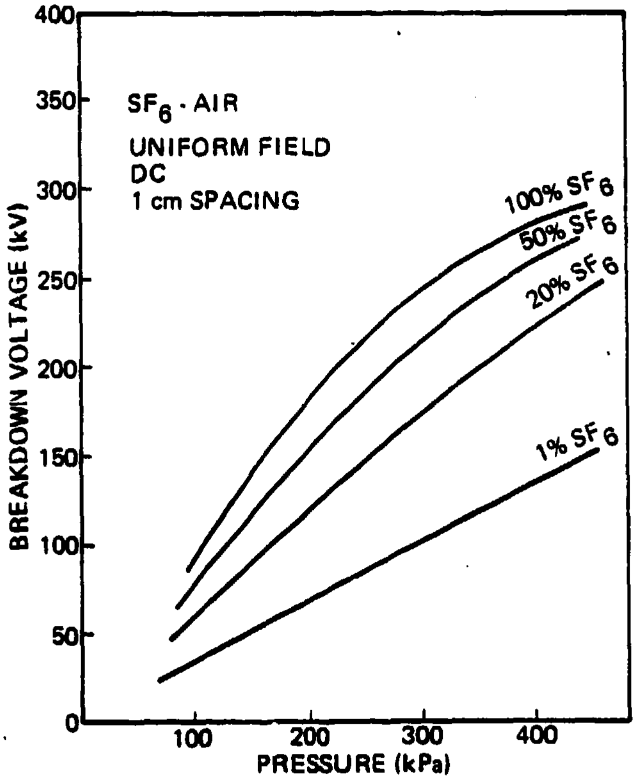


FIGURE 11B BREAKDOWN VOLTAGES AS A FUNCTION OF GAS PRESSURE FOR SF_6-AIR MIXTURES

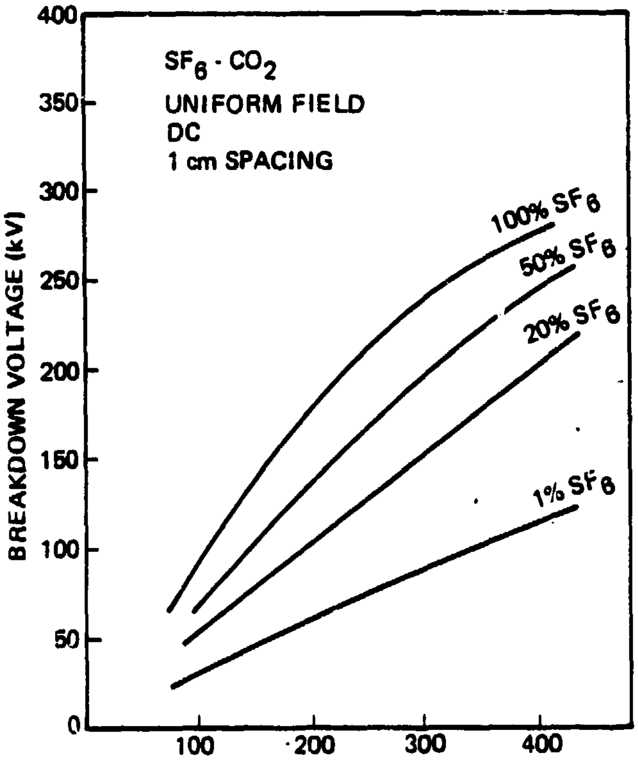


FIGURE 11C BREAKDOWN VOLTAGES AS A FUNCTION OF GAS PRESSURE FOR SF_6-CO_2 MIXTURES

Experiments are underway by Christophorou et. al [22] on ernary gas dielectrics as a replacement or additive to SF_6 mixtures. When used, the ternary mixture is composed of one electron moderating gas like nitrogen on CHF_3 and two electron-attaching gases like SF_6 and PFC. A list of these mixtures with their breakdown voltages compared to 100% SF_6 between cylindrical electrodes at direct voltage is shown in Table 5. A drawback to the ternary gases are their cost and abundance. Advantages are that less carbon is formed when the mixture is sparked, some of the PFC's have dielectric strength as much as two times that of SF_6, and increases both the positive and negative pulse withstand voltage.

The dew point of a gas mixture is important for pressurizing gases. The measured dew points for SF_6-N_2 mixtures [23] are shown in Table 6. Most military applications require a dew point less than -55°C, otherwise heaters must be installed in the equipment to prevent condensation of the gas.

Table 6: SF_6/N_2 Mixture Dew Points (°C)

Composition (Vol. %)	Loading Pressure at 25°C		
SF_6/N_2	1 atm	3 atm	5 atm
0/100	-110	-	-
20/80	-92.1	-77.1	-68.9
40/60	-82.4	-66.9	-57.3
60/40	-76.7	-59.6	-50.5
80/20	-72.8	-54.7	-44.1
100/0	-68.7*	-50.1	-37.7

*Represents sublimination point.

21. N. H. Malik and A. H. Qureski, "Breakdown Characteristics on SF_6-N_2, SF_6-Air, and SF_6-CO_2 Mixtures", IEEE, Trans. on Elec. Insulation, Vol. EI-15, No. 5, Oct. 1980, pp 413-418.

22. L. C. Christophrou, D. R. James, I. Sauers, M. O. Pace, R. Y. Rai and A. Fatheddin, "Ternary Gas Dielectrics", IEEE, Third International Symposium on Gaseous Dielectrics, March 1982, p. 13.

TABLE 5

DC VOLTAGE BREAKDOWN OF TERNARY GAS DIELECTRICS BETWEEN COAXIAL CYLINDERS AT ONE ATMOSPHERE

V_s = DC Voltage Breakdown Ratio: $\frac{\text{Gas Mixture}}{SF_6}$

No.	TERNARY GAS DIELECTRIC	V_s
1	80% N_2 + 15% SF_6 + 5% 2-C_4F_6	0.86
2	70% N_2 + 25% SF_6 + 5% 2-C_4F_6	0.91
3	60% N_2 + 35% SF_6 + 5% 2-C_4F_6	0.97
4	65% N_2 + 25% SF_6 + 10% 2-C_4F_6	0.96
5	50% N_2 + 40% SF_6 + 10% 2-C_4F_6	1.04
6	40% N_2 + 30% SF_6 + 30% 2-C_4F_6 (3-4 Atm)	1.12
7	80% N_2 + 15% SF_6 + 5% c-C_4F_8	0.84
8	70% N_2 + 25% SF_6 + 5% c-C_4F_8	0.88
9	70% N_2 + 20% SF_6 + 10% c-C_4F_8	0.89
10	60% N_2 + 35% SF_6 + 5% c-C_4F_8	0.93
11	40% N_2 + 30% SF_6 + 30% c-C_4F_8	1.08
12	50% N_2 + 40% SF_6 + 10% c-C_5F_9	1.00
13	50% N_2 + 40% SF_6 + 10% c-C_6F_{10}	1.05
14	60% CHF_3 + 20% SF_6 + 15% c-C_4F_8	0.92
15	40% CHF_3 + 30% SF_6 + 30% 2-C_4F_9 (1-3 Atm)	1.14
16	40% CHF_3 + 30% SF_6 + 30% c-C_4F_8 (3-4 Atm)	1.09
17	SF_6	1.00

Electrode Materials. Electrode materials do affect the breakdown voltage. For parallel plane electrodes, the dielectric strength is a function of the mechanical strength, the material melting temperature, and the work function.[20] The effect is most noticeable on the cathode material; the anode material has little effect.

Electrode Effects. Maximum voltage breakdown is attained with uniform fields between Rogowski shaped electrodes. Smaller radii on the electrodes will decrease the breakdown voltage as shown in Figure 12.

Experiments by Rohlfs and Kennedy[24] show the effects of electrode radius. They mounted two 50 cm dia discs of various thickness in a test fixture. The ground disc was mounted horizontal to the surface, the high-voltage disc was mounted perpendicular to the surface of the ground disc, such that the edge radius of the high voltage disc served as an electrode. In addition, these discs were tested as either bare aluminum electrodes or as polymer film coated aluminum electrodes. The test results are shown in table 6 for power frequencies, pulse voltage (1.4 x 52 μs) bare and coated electrodes. It was shown that coating the electrodes increased the breakdown voltage 10 to 15%.

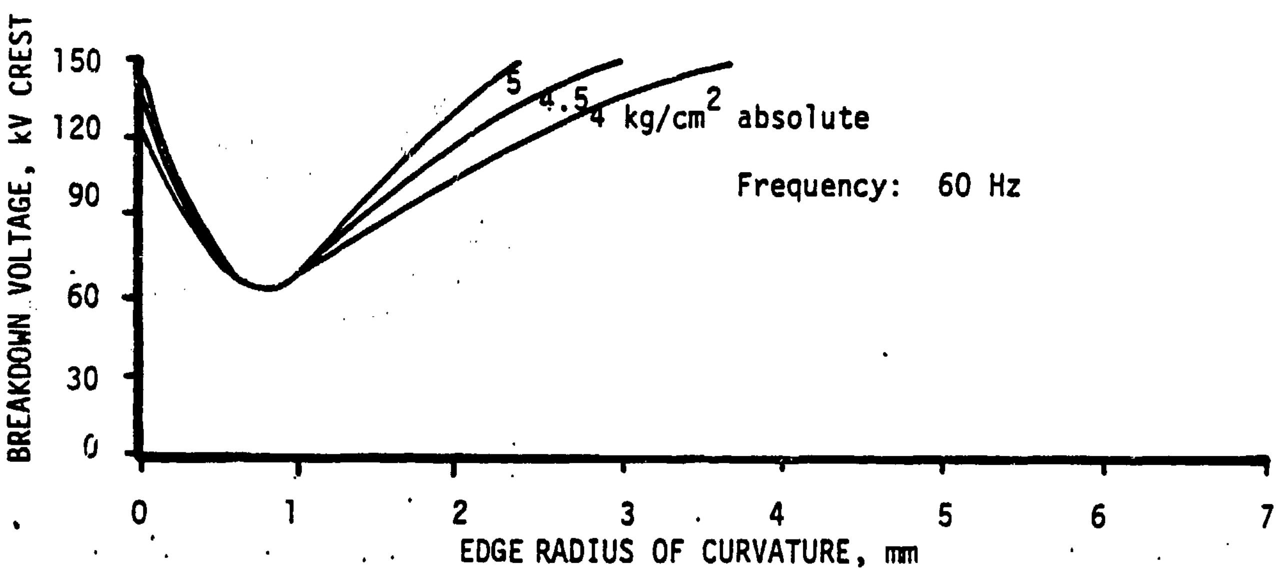


FIGURE 12 BREAKDOWN VOLTAGE AT 60 HZ FOR ROGOWSKI ELECTRODES

Experimental Figures 13 and 14 show measured breakdown voltages for polyurethane-coated and anodized-aluminum electrodes for the gas pressures and thicknesses indicated.[25] This technique for increasing breakdown voltage is not recommended unless the coating materials are given sufficient life testing and the coating process is held to a very tight tolerance. The use of coatings applied to the electrodes can be recommended for improving the safety margin. However, a coating that becomes unbonded will flake or blister, lowering the breakdown voltage to values lower than that of bare electrodes.

The effect of particles entrapped between electrodes was demonstrated by placing small spheres or short tubes between energized electrodes by Cookson and Wootton.[26,27,28] Small lengths of copper between coaxial conductors (Figures 15 and 16) shows that the breakdown voltage decreases as the length is increased. This explains why small particles between energized electrodes decrease the breakdown voltage significantly.

25. D. J. Chee-Hing and K.D. Srivastava, "Insulation Performance of Dielectric-Coated Electrodes in Sulphur Hexafluoride Gas", IEEE, Trans. on Elec. Insulation, Vol. EI-10, No. 4, December 1975, pp. 119-124.

26. A. H. Cookson and O. Farish "Motion of Spherical Particles and AC Breakdown in Compressed SF_6", Conf. on Elec. Insulation and Dielectric Phenomena, 1971 Annual Report, National Academy of Sciences, Washington, D C., pp. 129-135.

27. A. H. Cookson and R. E. Wootton, "Particle-Initiated AC and DC Breakdown in Compressed Nitrogen, SF_6, and Nitrogen-SF_6 Mixtures", Conf. on Elec. Insulation and Dielectric Phenomena, 1973 Annual Report, National Academy of Sciences, Washington, D.C., pp. 234-241.

28. C. M. Cooke and A. H. Cookson, "The Nature and Practice of Gases as Electrical Insulation", IEEE, Trans. on Elec. Insulation, Vol. EI-13, No. 4, August 1973, pp. 239-247.

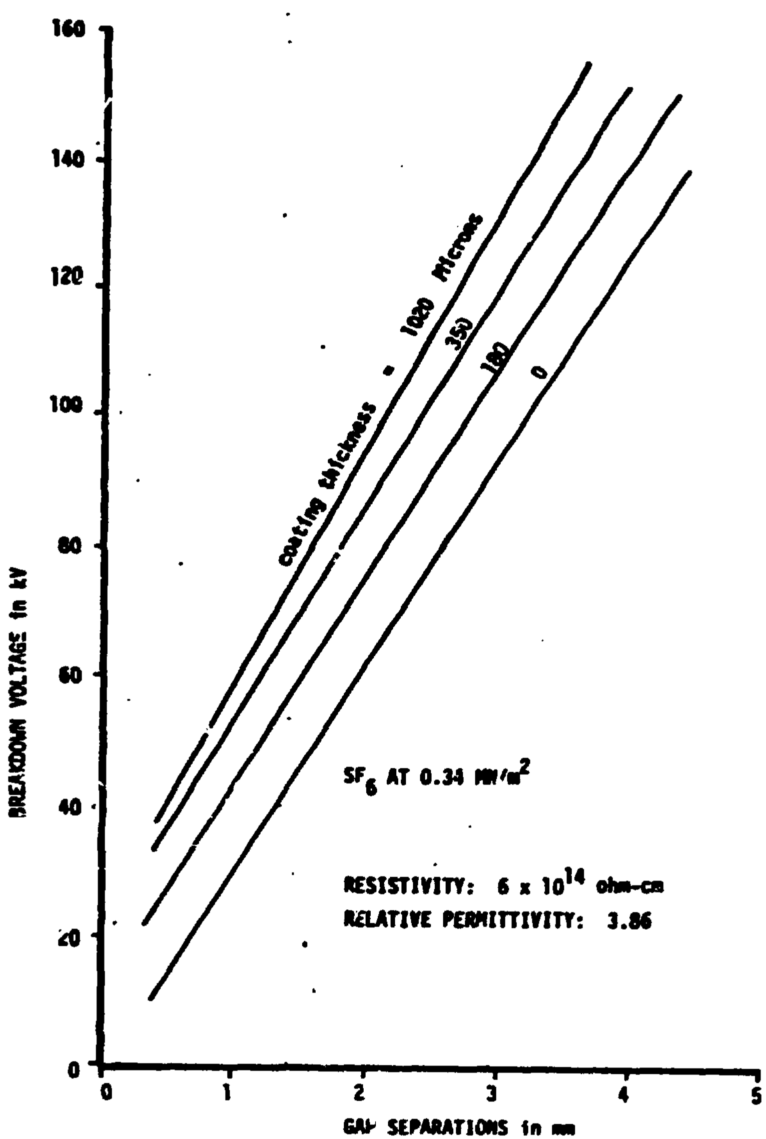


FIGURE 13 UNIFORM FIELD PERFORMANCE OF UNLOADED POLYURETHANE COATED ELECTRODES UNDER DC VOLTAGES

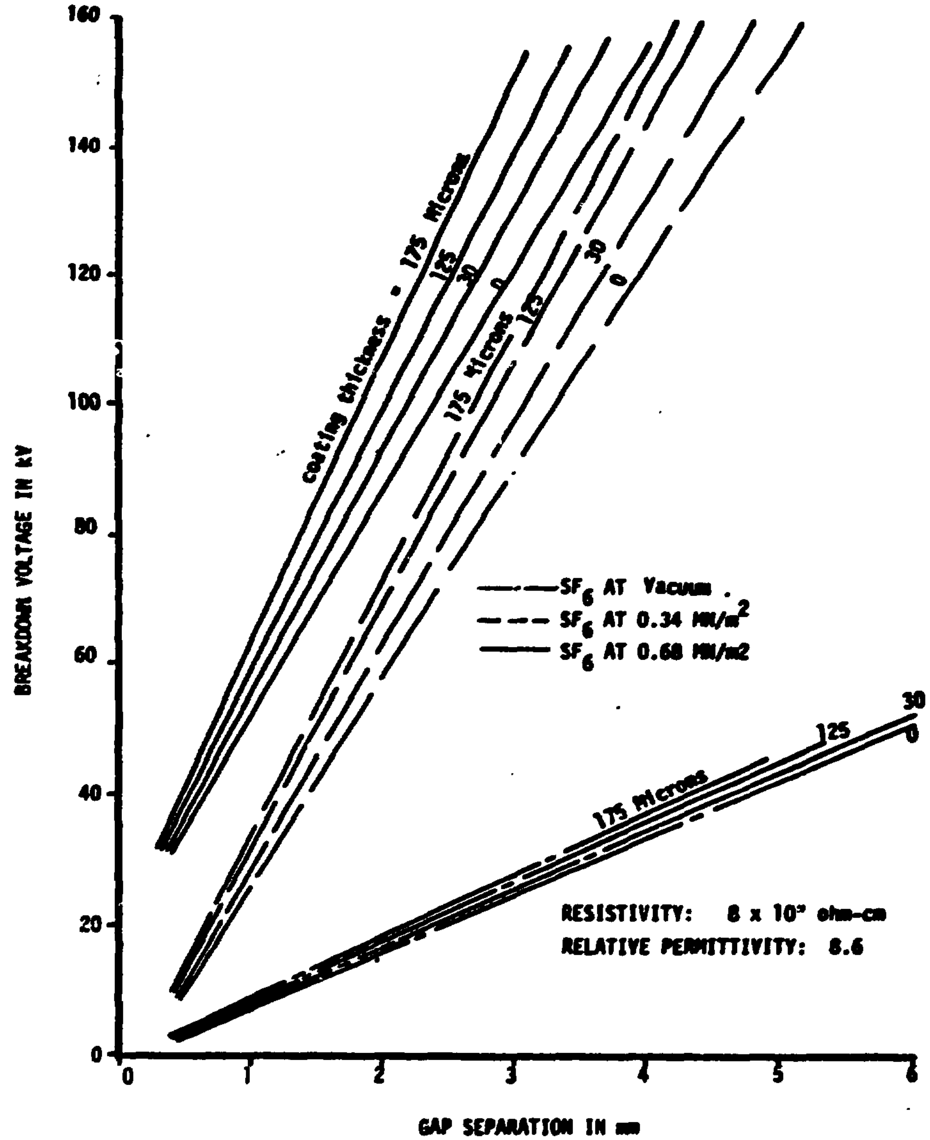


FIGURE 14 UNIFORM FIELD PERFORMANCE OF ANODIZED ALUMINUM ELECTRODES UNDER DC VOLTAGES

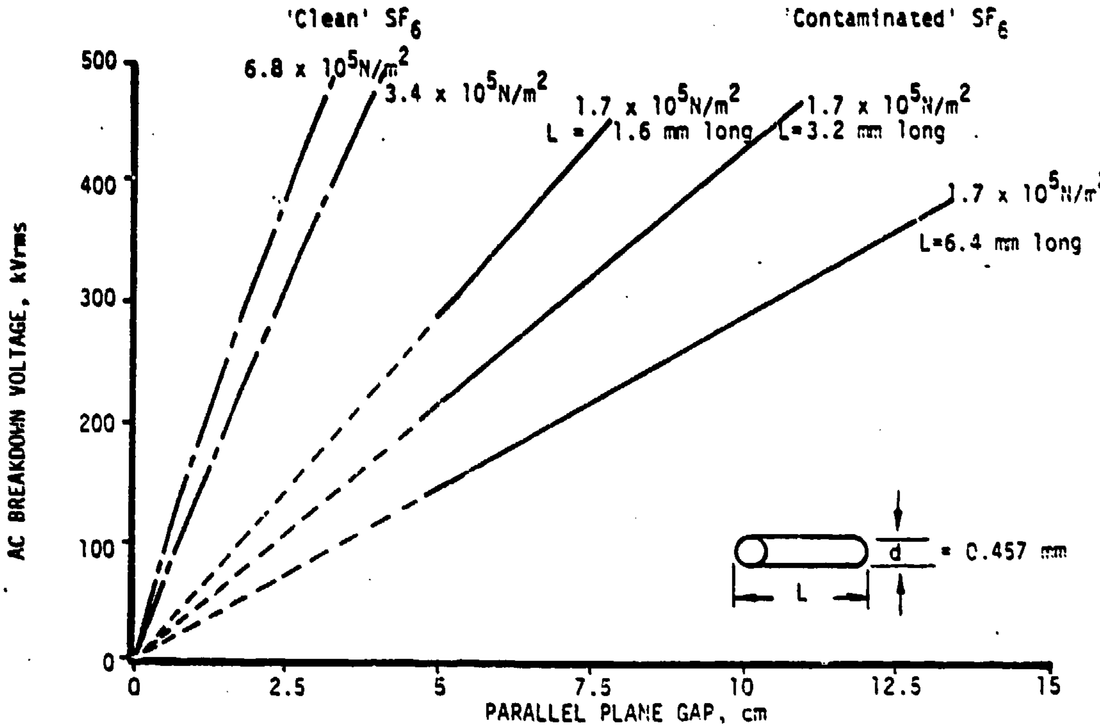


FIGURE 15 AC BREAKDOWN VOLTAGE-GAP CHARACTERISTICS IN SF_6 WITH COPPER PARTICLES OF VARIOUS LENGTH

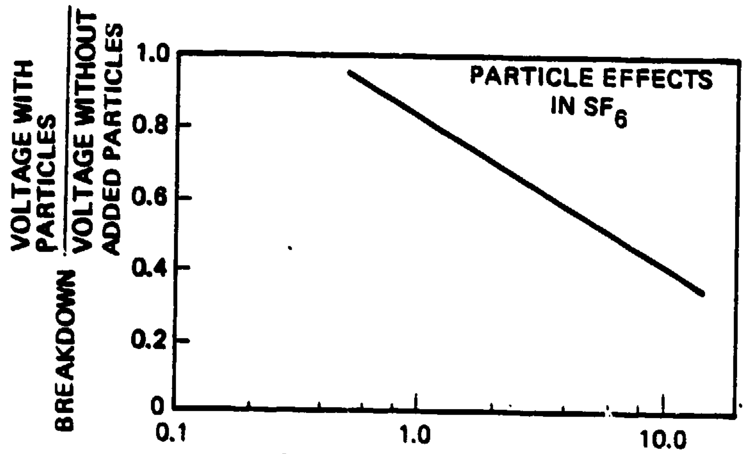


FIGURE 16: REDUCTION IN SF_6 BREAKDOWN VOLTAGE DUE TO CONDUCTING PARTICLES AT 1 ATMOSPHERE

5.1.7 <u>Voltage Transients and Time Lag</u>. The statistical time lag is the time needed for a triggering electron to appear in a gas filled gap. The tip of a breakdown streamer travels at about 10^{-8} cm/s . The return stroke is somewhat faster. This implies that streamer breakdown should occur within 10^{-8} s after applicaton of breakdown potential, provided adequate triggering electrons are present.

The time to breakdown varies with applied voltage, the gas pressure, the electrode configuration, and the spacing between electrodes. Curves showing the ratio impulse voltage to steady-state breakdown voltage for three electrode configurations in air at one atmosphere pressure are shown in Figure 17. These curves show that very fast, short-duration transients (less than 10 nanoseconds) will not cause breakdown at overvoltages less than 150 percent of steady-state breakdown voltage. Slow transients (less than one microsecond duration) require 105 to 110 percent of steady-state voltage for breakdown. Thus, the transient voltage peak and duration are an important element in estimating the probability of breakdown between electrodes of known configuration.

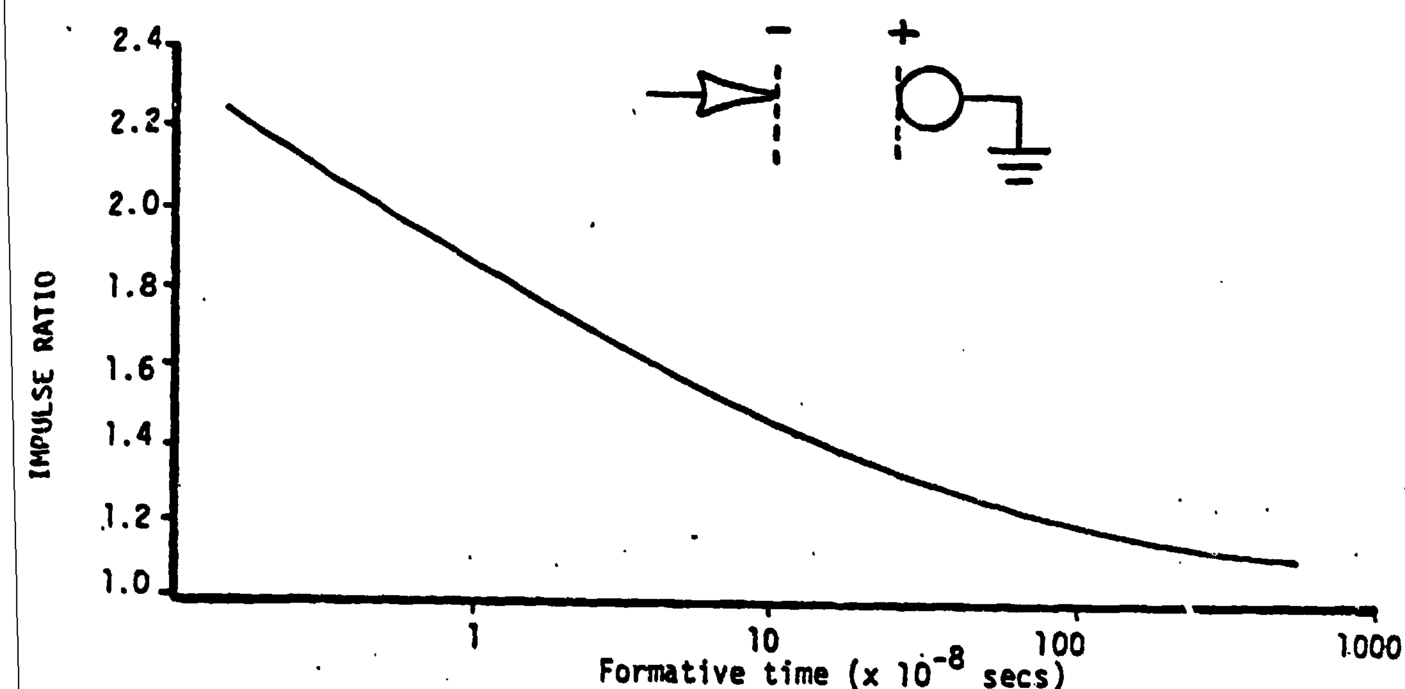


FIGURE 17 RELATION BETWEEN FORMATIVE TIME AND IMPULSE RATIO FOR VARIOUS GAP LENGTHS AND GAS PRESSURE IN A NEGATIVE POINT-SPHERE GAP IN AIR.

5.2 <u>Solid Insulation</u>. Ideally, a solid insulation has no conductive elements, no voids or cracks, and has uniform dielectric properties. Practical insulations have thickness variations, may shrink with temperature and age, may have some deposited conductive elements, and their dielectric properties change with temperature, frequency, and mechanical stresses.

In aircraft applications the environmental and electrical stresses vary as a function of time; some independently, others dependent upon each other. These variations make it difficult to select an ideal insulation for a specific application. Furthermore, it isn't possible to extrapolate the operation of a second or third generation device based upon the performance of a first generation device. For instance, the composition of materials varies from batch-to-batch, and the cleanliness and manner of handling and manufacturing in a production facility are not the same as in a prototype shop. All these matters must be considered when developing an insulation for a new high-voltage product.

The pertinent environmental and electrical characteristics of solid insulations are discussed below.

5.2.1 <u>Materials Properties</u>. Solid insulation has electrical, mechanical, thermal, and chemical properties. These and miscellaneous properties are detailed in Table 7. Sometimes materials are specified to be transparent so the packaging engineer can assess parts stressing and bonding. Weight, water adsorption, and outgassing are often specified. Most important for all categories of high-voltage insulation is life, which depends upon the electrical stress and environment.

TABLE 7

PROPERTIES OF INTEREST FOR INSULATING MATERIALS

MECHANICAL PROPERTIES	ELECTRICAL PROPERTIES	THERMAL PROPERTIES	CHEMICAL PROPERTIES	MISCELLANEOUS PROPERTIES
Tensile, compressive, shearing, and bending strengths	Electric strength	Thermal conductivity	Resistance to reagents	Specific gravity
Elastic moduli	Surface breakdown strength	Thermal expansion	Effect upon adjacent materials	Refractive index
Hardness	Liability to track	Primary creep	Electro-chemical stability	Transparency
Impact and tearing strengths	Volume and surface resistivities	Plastic flow	Stability against aging and oxidation	Color
Viscosity	Permittivity	Thermal decomposition,	Solubility	Porosity
Extensibility	Loss tangent	Spark, arc, and flame resistances	Solvent crazing	Permeability to gases and vapors
Flexibility	Insulation resistance	Temperature coefficients of other properties		Moisture Adsorption
Machinability	Frequency coefficients of other properties	Melting point		Surface adsorption of water
Fatigue		Pour point		Resistance to fungus
Resistance to abrasion		Vapor pressure		Resistance to aging by light
Stress crazing				

Dielectric strength, dielectric constant and the dissipation factor are the most readily measured electrical perperties. Dielectric strengths and dielectric constants are well documented for high voltage materials. Less data is available on the dissipation factor, also called loss tangent ($\tan\delta$), which is defined as:

$$\tan\delta = \frac{\sigma}{\omega\epsilon} = \frac{1}{Q} \tag{3.5}$$

where σ is the ac conductivity, and ω is the frequency in radians/s and

$$Q = 2\pi \frac{\text{average energy stored per half cycle}}{\text{energy dissipated per half cycle}} \tag{3.6}$$

Dissipation factor and dielectric constant both vary with frequency and temperature, a characteristic that should not be overlooked.

For a lossy dielectric, its admittance, Y, may be written

$$Y = G + jB \tag{3.7}$$

and for vacuum as a dielectric,

$$Y_0 = G_0 + JB_0$$

but $G_0 = 0$ in a vacuum, then

$$Y/Y_0 = B/B_0 = jG/B_0 = k^* = k' - jk'' \tag{3.9}$$

This ratio k^* is called the complex dielectric constant or permittivity. The quantity

$$B/B_0 = \omega C/\omega C_0 = \epsilon/\epsilon_0 = k' \tag{3.10}$$

and

$$G/G_0 = C/\omega C_0 = \sigma/\epsilon_0 = k'' \tag{3.11}$$

where C = capacitance.

A dielectric may have four abrupt changes in dielectric constant, the lowest value being at highest frequency and the highest value being at very low frequency, sometimes close to dc (Figure 18). Changes in the real part of the dielectric constant, k', are associated with significant change in the imaginary part of the dielectric constant, $-jk''$ or loss tangent.

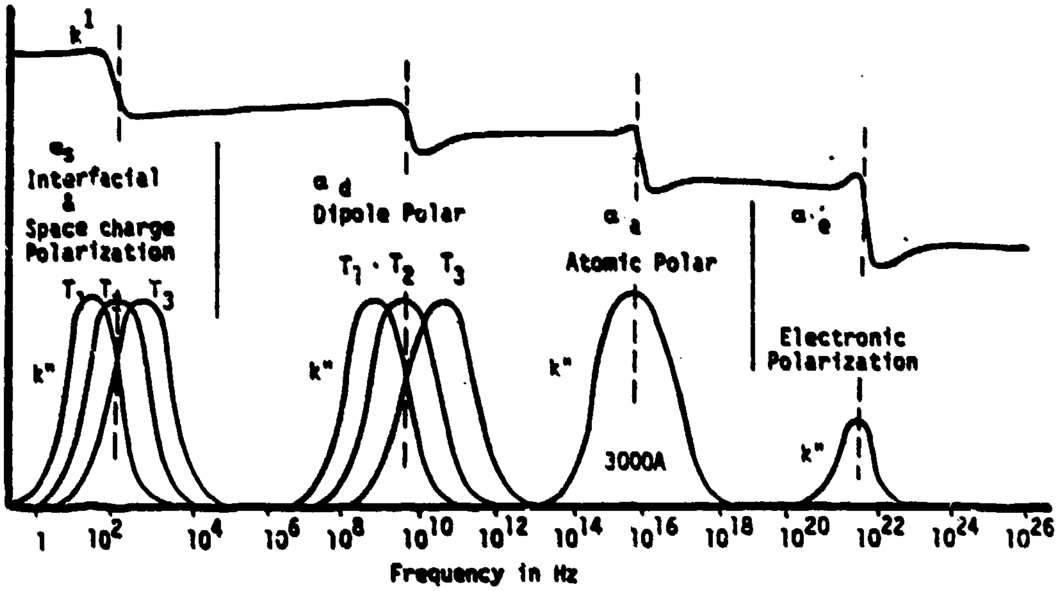


FIGURE 18 DIELECTRIC POLARIZATIONS

The sharp decreases in dielectric constant of course occur when the relaxation time of the particular polarization involved becomes equal or less than the periodicity of the applied field. That is when $\tau \leq \frac{1}{F}$. Under such circumstance the polarization has time to get well under way and contribute to the polarizability. Conversely, when $\tau \gg \frac{1}{F}$, the field reversals are too rapid and a polarization with that time constant mechanism cannot contribute to polarizability or, what is the same thing, to the observed dielectric constant. In general, α_s is effective up to several thousand cycles per second; α_d can be effective from 10^4 up to 10^{12} Hz, and even this wide range can be increased further into the low frequency area by reducing temperatures; α_a shows up in the infra-red spectrum and α_e in the optical region and above.

A high loss tangent means the dielectric will heat when voltage is applied, so the thermal conductivity of the material must be determined and a heat-balance calculation must be made to predict insulation hot-spot temperatures. Hot spots are where the insulation life will first be exhausted.

Frequency determining electronic circuits, if operated near the frequency singularities, can be affected by fluctuating interelectrode capacitance changes. Good reference material about this phenomena can be found in References 29 and 30.

5.2.2 Materials Data Pamphlets. When selecting an insulating material for a high voltage application, the right data seems to be hard to find. Mechanical and chemical data are usually abundant but too often the available electrical data is a simple tabulation of constants, with no hint of how these constants will vary. Most published data needs to be adjusted or translated into the application at hand.

The electrical properties of polyimide film (Kapton) are shown in Table 8. These variations in dielectric strength, dielectric constant, dissipation factor, volume resistivity, surface resistivity, and corona susceptibility are described below for Kapton H, a DuPont polyimide which is often used as a high-voltage insulation in aircraft. Throughout this paragraph English units of measurement are used to preserve consistency with the manufacturer's published data sheets.

Dielectric Strength. Typical values for the dielectric strength of Kapton H range from 7000 V/mil for a 1-mil film to 3600 V/mil for a 5-mil film, at 60 Hz, between 1/2-inch diameter electrodes in 23^{o}C air at one atmosphere pressure for one minute. These dielectric strengths are based on the statistical average breakdown of carefully manufactured polyimide films having the indicated thickness. These values cannot be used in equipment design because:

- Films vary in thickness within manufacturing tolerances.
- The composition of Kapton-H varies.
- The operating temperature will not be 23^{o}C

29) A.R. Von Hippel, Dielectric Materials and Applications, John Wiley and Sons, Inc., New York, New York, 1954.

30) E.W. Greenfield, Introduction to Dielectric Theory and Measurements, Washington State University, Pullman, Washington, 1972.

TABLE 8

TYPICAL ELECTRICAL PROPERTIES OF POLYMIDE FILM AT $23^{o}C$ AND 50% RELATIVE HUMIDITY

PROPERTY	TYPICAL VALUE	TEST CONDITION	TEST METHOD
Dielectric Strength			
1 mil	7,000 v/mil	60 cycles	ASTM
2 mil	5,400 v/mil	¼" electrodes	D-149-61
3 mil	4,600 v/mil		
5 mil	3,600 v/mil		
Dielectric Constant			
1 mil	3.5	1 kilocycle	ASTM
2 mil	3.6		D-150-59T
3 mil	3.7		
5 mil	3.7		
Dissipation Factor			
1 mil	.0025	1 kilocycle	ASTM
2 mil	.0025		D-150-59T
3 mil	.0025		
5 mil	.0027		
Volume Resistivity			
1 mil	1×10^{18} ohm-cm	125 volts	ASTM
2 mil	8×10^{17} ohm-cm		D-257-61
3 mil	5×10^{17} ohm-cm		
5 mil	1×10^{17} ohm-cm		
Corona Threshold Voltage			
1 mil	465 volts	60 cycles	ASTM
2 mil	550 volts	¼" electrodes	1868-61T
3 mil	630 volts		
5 mil	800 volts		
5 mil H/2 mil FEP/ 5 mil H/½ mil varnish	1,600 volts		

- Voltage transients must be considered.
- Field stress with other electrode shapes is different.
- The end-of-life dielectric strength is lower.

A more complete definition of the dielectric strength of Kapton-H is provided in Figures 19, 20, and 21. The effect of temperature on dielectric strength is shown in Figure 19. In aircraft applications, the highest operating temperature for a unit is usually specified, for example

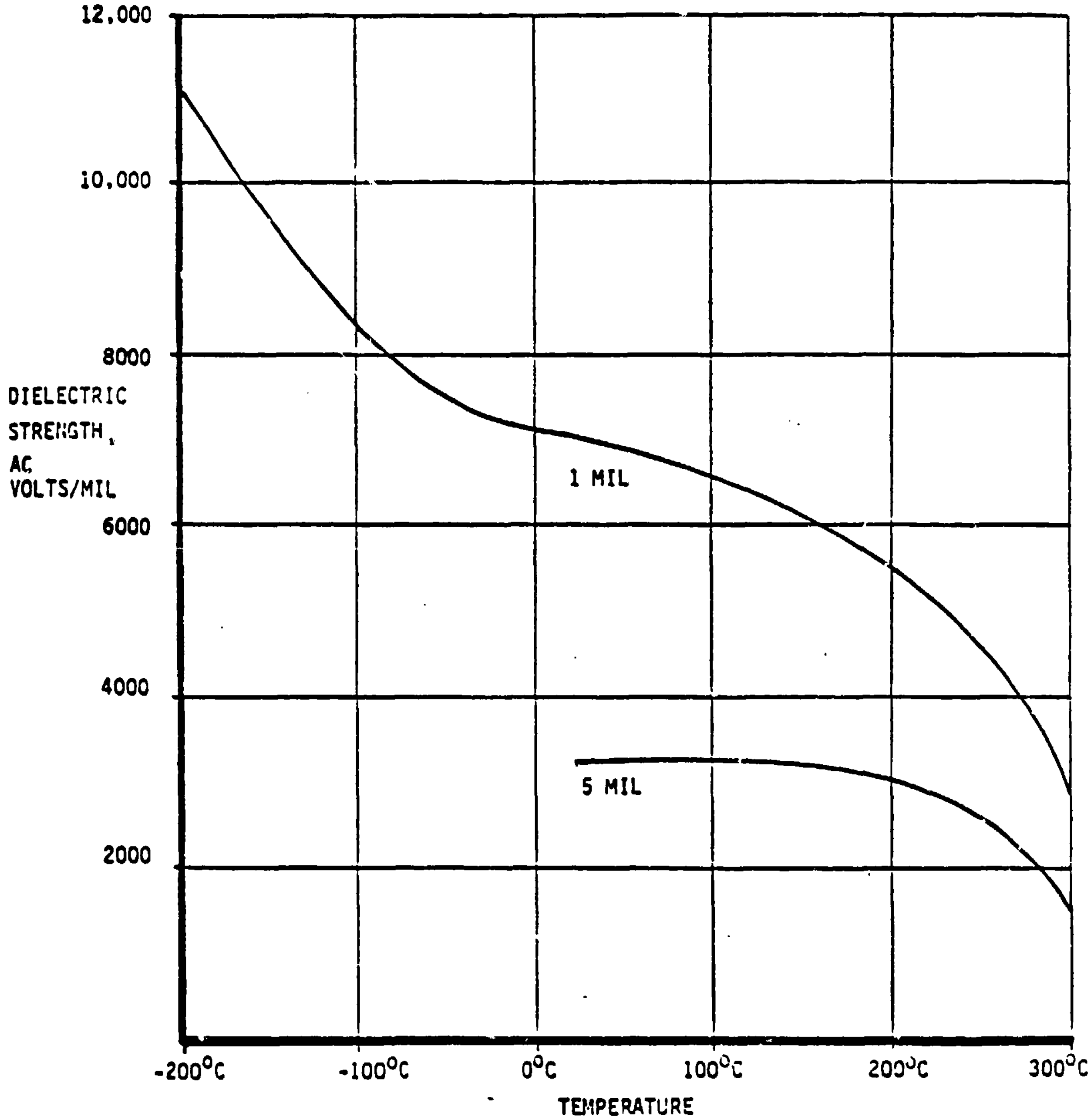


FIGURE 19. TEMPERATURE AFFECTS AC DIELECTRIC STRENGTH-TYPE H KAPTON FILM

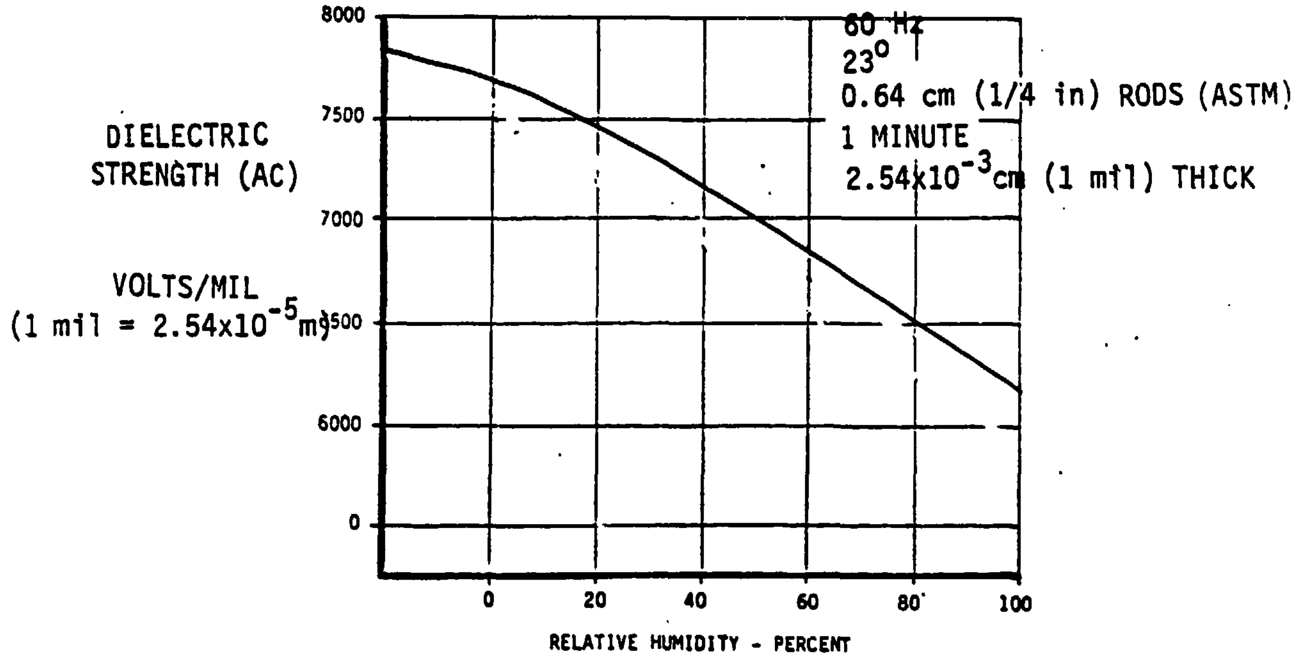


FIGURE 20 HIGH HUMIDITY DEGRADES THE DIELECTRIC STRENGTH OF TYPE H KAPTON FILM

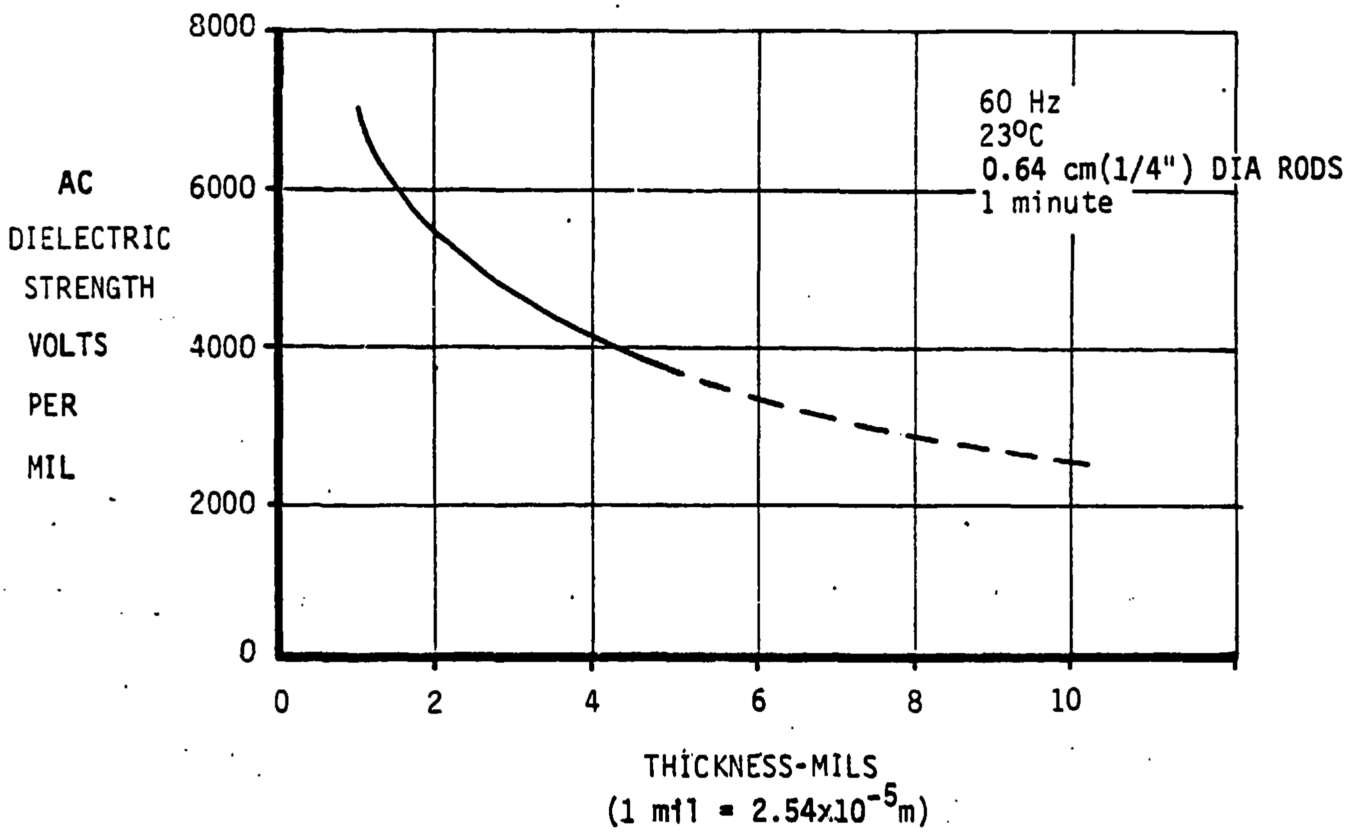


FIGURE 21 INSULATION THICKNESS AFFECTS DIELECTRIC STRENGTH OF TYPE H KAPTON FILM

at $85^{o}C$. This is not the insulation design value! The insulation design temperature must be that of the hottest point within the equipment. An electrically insulated heat-generating element will operate at a temperature which is sufficiently hotter than ambient to drive the generated heat through the insulation. For instance, the hot spot within the slot insulation of an electrical machine may be $20^{o}C$ higher than the nominal temperature in the machine. Such "hot spots" are created by high current densities in wiring and heat generating mechanisms in the insulation itself. It is obvious from Figure 19 that an extra $20^{o}C$ may lower the dielectric strength considerably when the insulation is either thin or operated at temperatures above $200^{o}C$.

Relative humidity also affects the dielectric strength of Type-H Kapton as shown in Figure 20. For this reason, very high-voltage equipment is often packaged in sealed containers back-filled with a dry dielectric gas such as sulfur hexafluoride. Generally, insulation in dry gas has higher dielectric strength than in moist gas. Dielectric strength tests are usually made at near 50% relative humidity.

Many insulations outgas into the surrounding media with time and heat. Often one of the outgassing products is water, which will raise the relative humidity of the gas and may even contribute to the formation of acids in the enclosure.

Most insulation test samples are either 1 mil or 5 mils thick. In high voltage work, thin insulation doesn't have enough dielectric strength so composite insulations having several layers of thin insulation are required. The dielectric strength of insulation decreases with thickness, as shown in Figure 21.

Active area of insulation is a factor often neglected in literature and data sheets. For areas of a few square centimeters, the effect is small, usually requiring less than 5% derating. For large areas, the required derating is considerable, as shown in Figure 22. This loss of dielectric strength is caused by roughness of electrode surfaces and non-uniform thickness of the manufactured insulation.

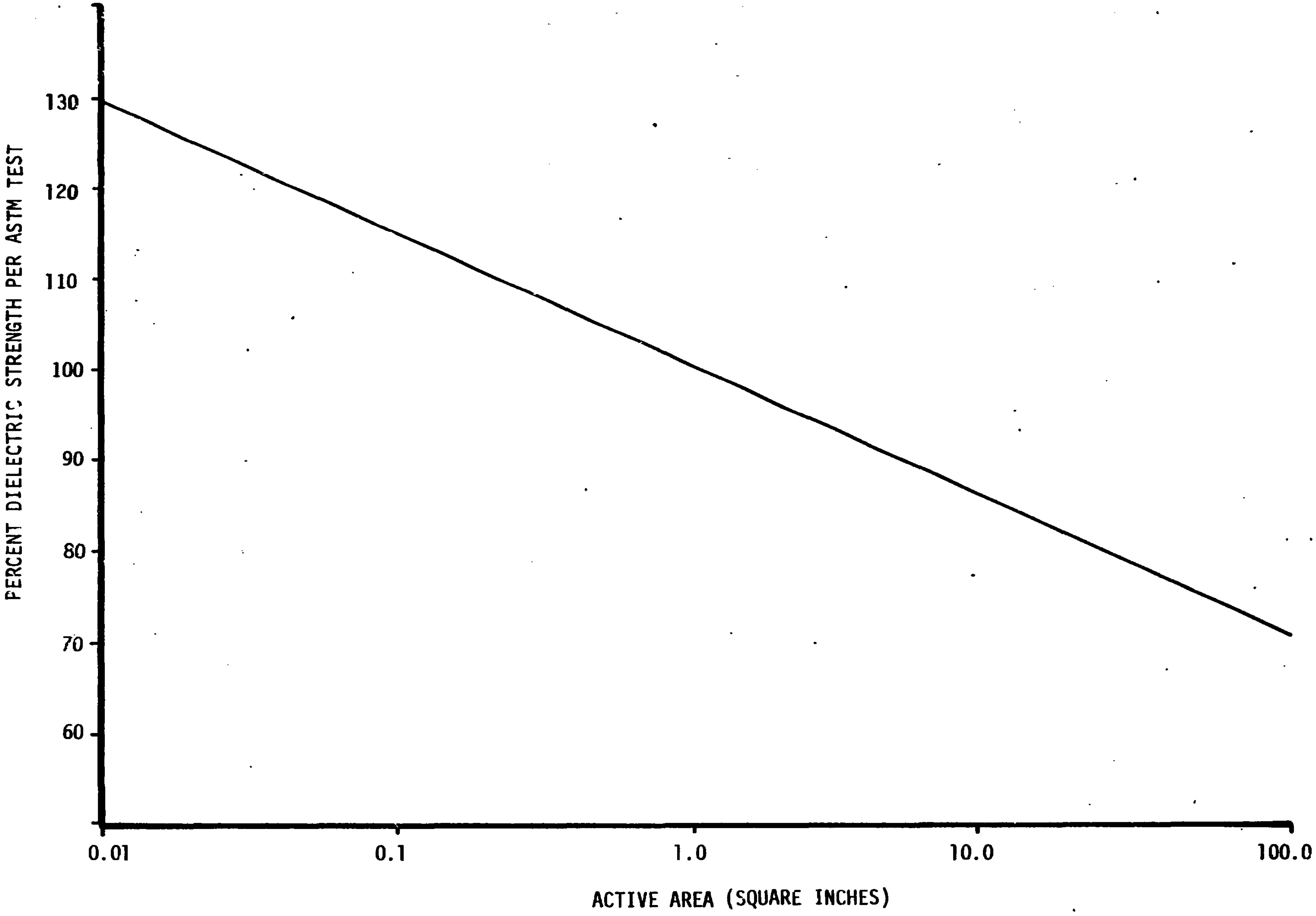


FIGURE 22 FILM AREA VS DIELECTRIC STRENGTH OF TYPE H KAPTON

Insulation Life. Finally, the most important factor in high voltage insulation design is the life of the material. Each year many technical papers are published on the measurement of life factors, the deviations associated with the test data, and the preconditioning of test samples. All these significant factors must be considered. However, the des... ...r often has difficulty in finding data other than from one minute tests at 23°C and 60 Hz between 1/2 inch diameter electrodes. Such tests tell little about the long-life characteristic of the material. The life of Type-H Kapton Polyimide is shown in Figure 23 for film exposed and not exposed to partial discharges. With the exposed samples, partial discharges were present whenever the initiation voltage of 465 volts was exceeded.

The characteristic life of a material can be evaluated as a function of temperature when available data are plotted as an Arrhenius plot with long life on the abscissa and the reciprocal of the absolute temperature on the ordinate (Figure 24). Life as a function of temperature is determined by measuring the breakdown at 50 percent of the one-minute level. Data for the life-temperature plot is taken as follows: 1) numerous samples are kept at constant test temperatures, 2) periodically a few samples are withdrawn and their breakdown voltages are measured, 3) when the statistically developed breakdown voltage of the withdrawn samples is 50 percent of the initial one-minute breakdown voltage, the end-of-life is assumed to be reached for the specific sample and its temperature. The life test must be conducted at several temperatures; therefore, much testing is required to gain this important information.

Dielectric strength has been shown to vary with temperature, time, thickness, area, and humidity. An example will illustrate how these variations affect design. Consider a one-mil-thick Kapton insulation between parallel plates operating at a voltage below that at which corona starts. This insulation is 100 square inches in area, its "hot spot" temperature is 200°C, relative humidity is zero, anticipated life is 1000 hours, and the frequency is 400 Hz. The maximum allowable applied voltage across the insulation can be calculated as follows:

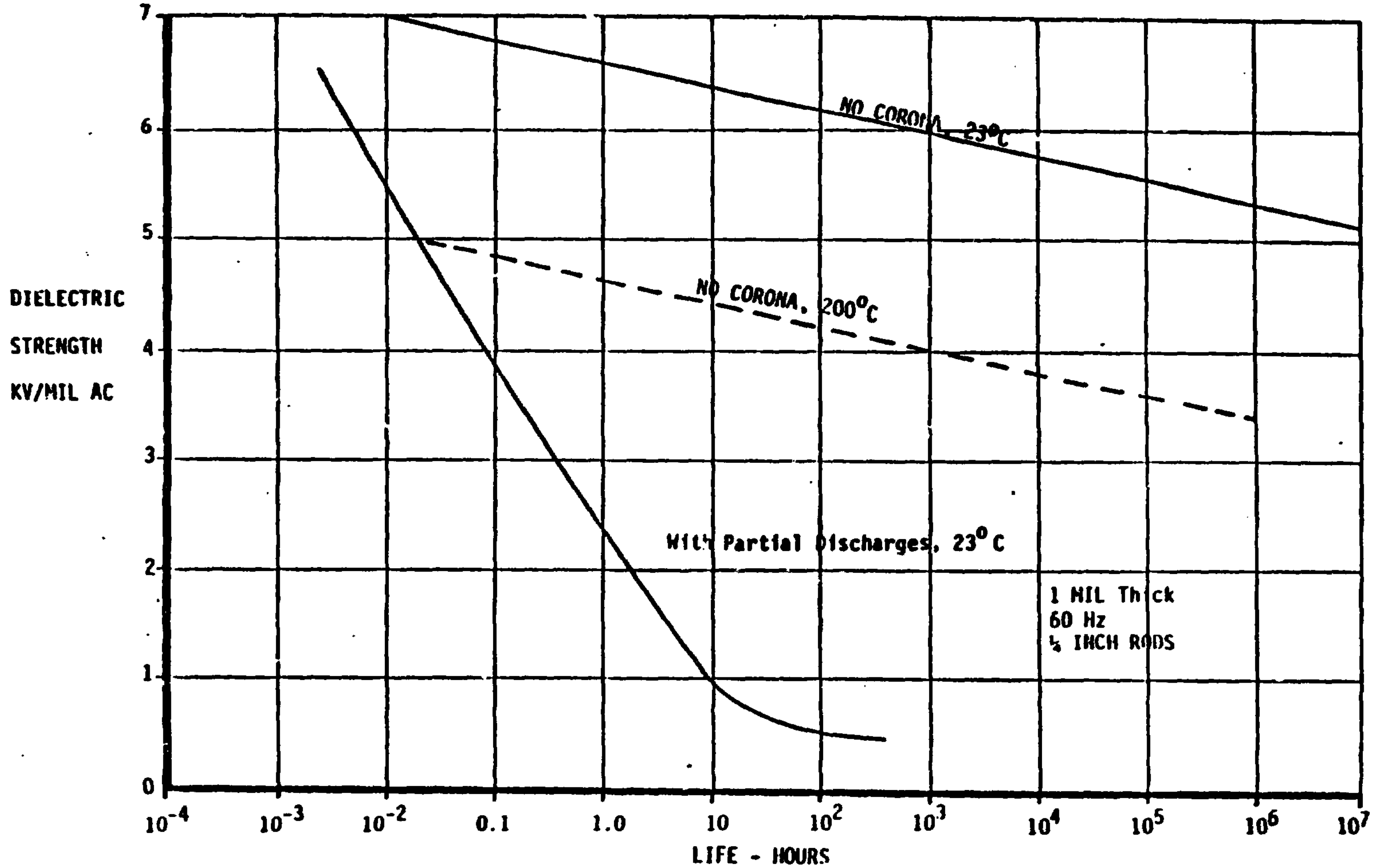


FIGURE 23. LIFE AS A FUNCTION OF VOLTAGE FOR TYPE H KAPTON FILM

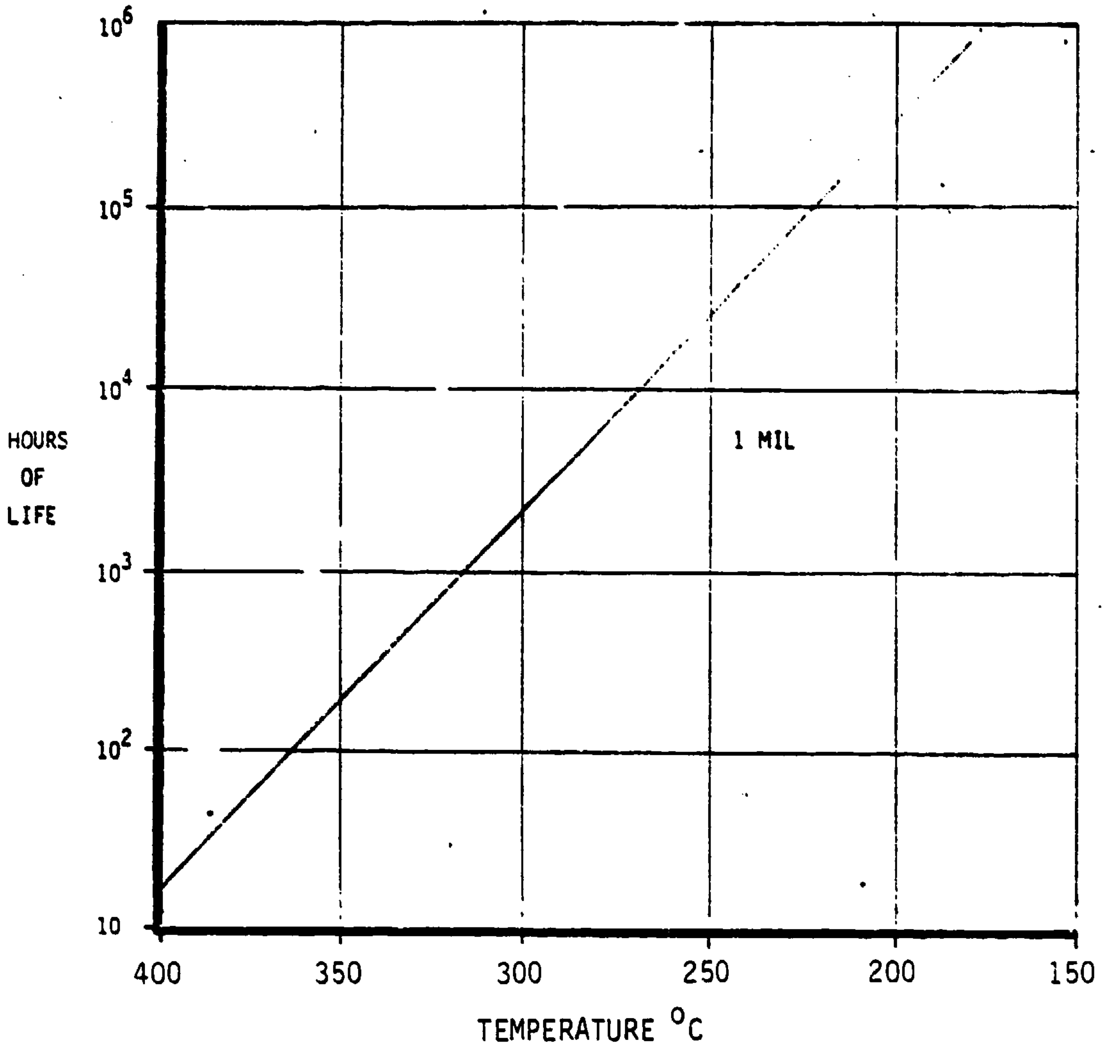


FIGURE 24. HEAT REDUCES THE TIME FOR KAPTON TYPE H FILM TO FALL TO HALF OF ORIGINAL DIELECTRIC STRENGTH

Baseline: Dielectric Strength = 7000 V per mil for 1 square inch at 23^oC, 50% RH and 60 Hz.

Factor		Effect
(ΔT)	Thickness (1 mil)	(FIGURE 21)
(ΔH)	Relative humidity (operate)	1.1 (Figure 20)
(ΔA)	Area (100 sq. inches)	0.71 (Figure 22)
(ΔF)	Frequency 60/400	0.15 that of 60 Hz life
($\Delta\bar{E}$)	dielectric strength, 1000 Hrs	6000 = 0.857 (Figure 23)
Life $\Sigma\Delta(T,H,A,F)\bar{E}$		700 volts/mil (Base voltage times product of factors)

Factor	Effect	
(ΔI) Impurities (inclusions)	0.66 (particulate)	
(ΔM) Manufacturing and handling	0.925	typical values
(ΔL) 2σ life (standard deviation)	0.66	
Voltage - Product of:	Life times factors 700 x 0.403 = 283 volts for a 1 mil thick Kapton film.	

One factor not included in the above is the degradation during application of the insulation to the electrodes. Application effects include damage to the insulation by mechanical bending, twisting, cleansing, and placing it on or between the electrodes. The value of the application factor should be lower for dielectrics that must be forced into final position, such as winding insulation that is forced into tight slots.

Dielectric Constant and Dissipation Factor. The effects of frequency on the value of the dielectric constant and dissipation factor at several temperatures are shown in Figures 25 and 26. There are frequency ranges at which the dissipation factor is high and the dielectric constant varies. Sometimes the dielectric must be operated in a regime where the dielectric constant and dissipation factor are constant to avoid dielectric heating and interelectrode capacitance changes. In such designs the operating temperature must be known because the dissipation factor and dielectric constant change with temperature.

Most measurements of dissipation factor are made at 1000 Hz and 23°C, whereas the insulation will be operated at 400 Hz to 20 kHz, and at 80° to 200°C. This leaves for the designer the problem of measuring the dissipation factor, searching for meaningful data, or extrapolating what data he has.

Resistivity. A high volume resistivity reduces heating of the dielectric. Values greater than 10^{12} ohm-cm are adequate for most power equipment. High-voltage insulations should have a volume resistivity greater than 10^{14} ohm-cm. Polyimides in high-voltage service should be operated at temperatures lower than 200°C, as suggested in Figure 27.

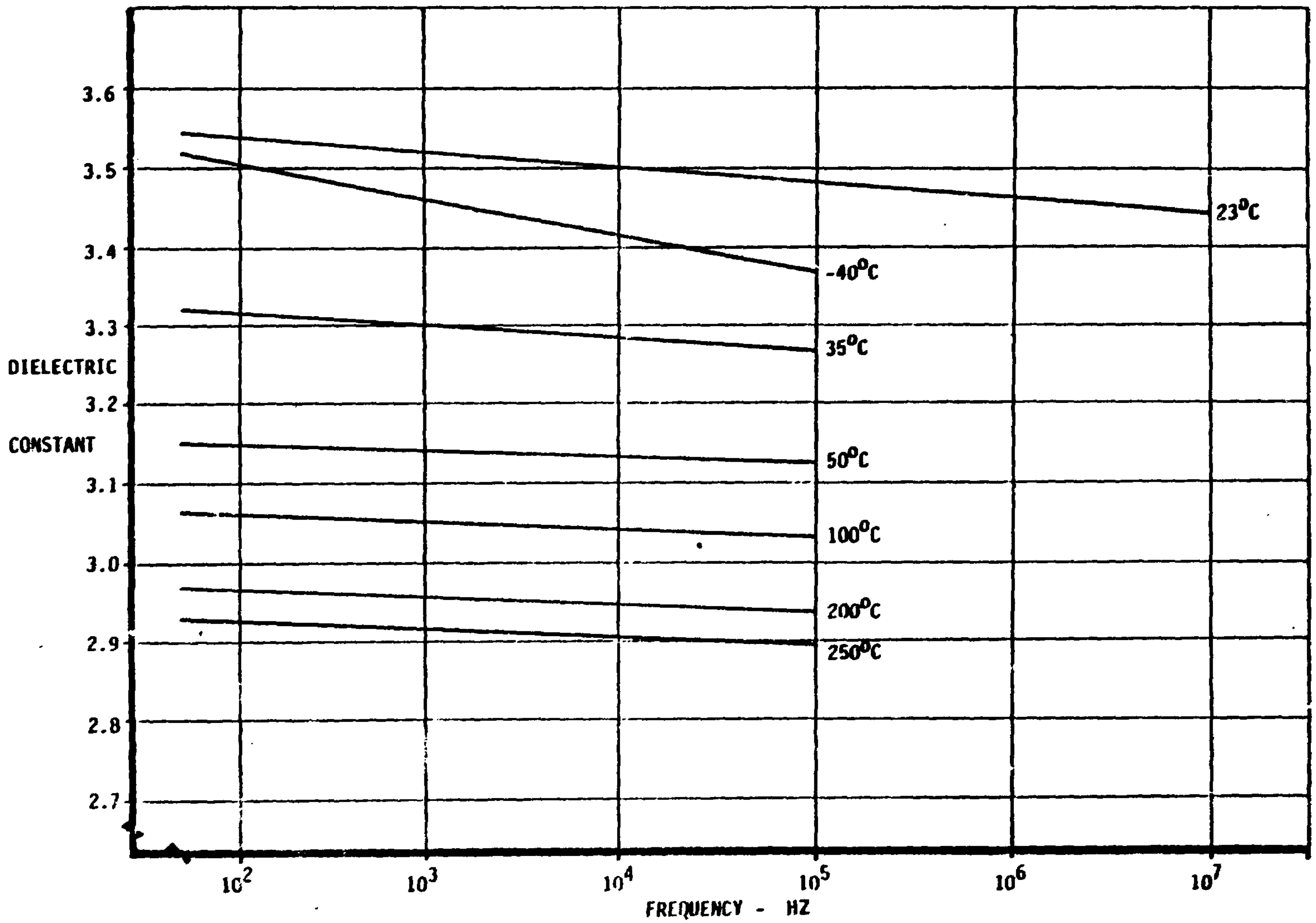


FIGURE 25. DIELECTRIC CONSTANT VS FREQUENCY FOR 1 MIL THICK TYPE H KAPTON FILM

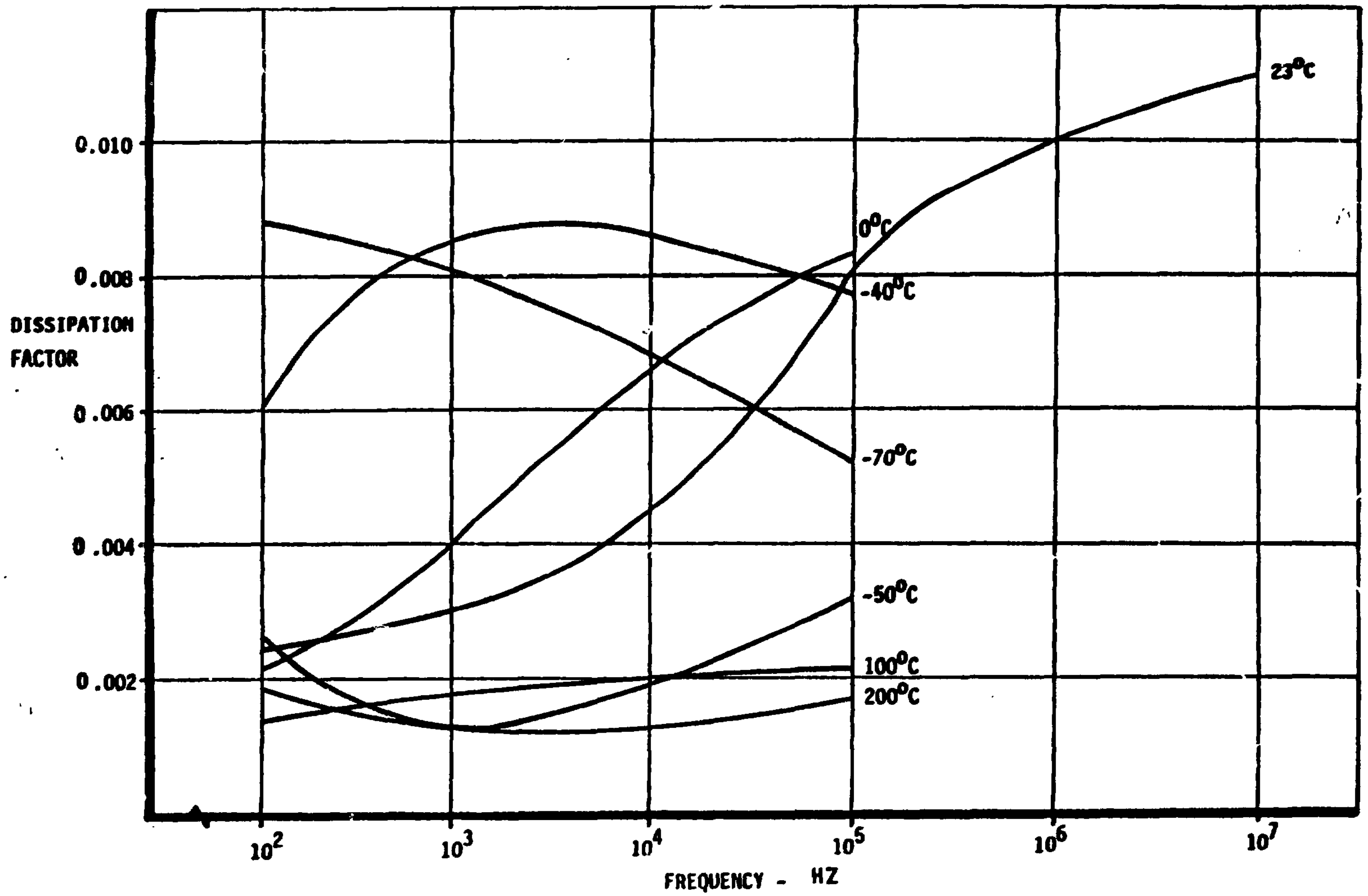


FIGURE 26 DISSIPATION FACTOR VS FREQUENCY FOR 1 MIL THICK TYPE H KAPTON FILM

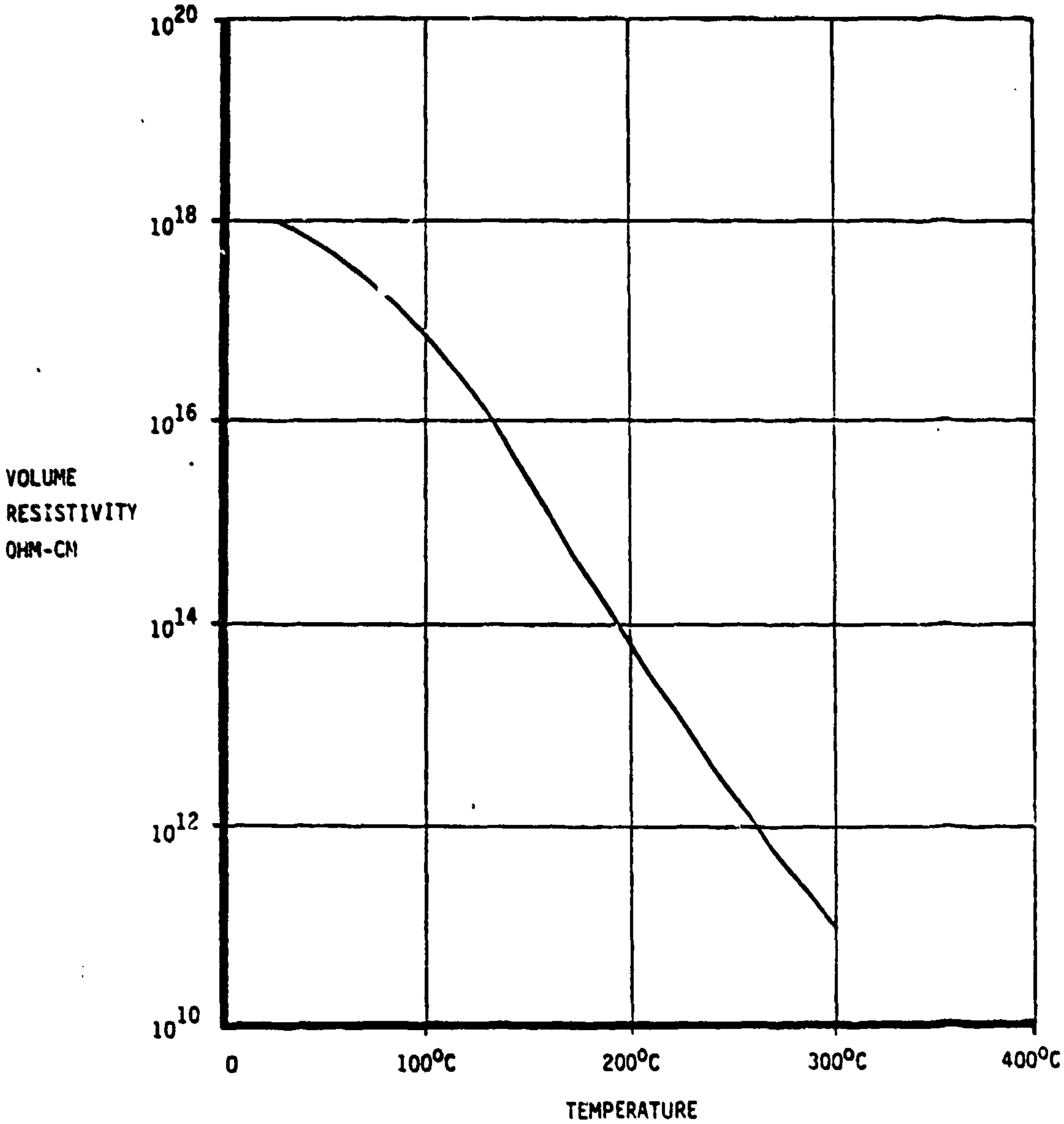


FIGURE 27. VOLUME RESISTIVITY OF TYPE H KAPTON FILM AT 1 KHZ DECREASES AS TEMPERATURE IS RAISED

Surface resistivity must be greater than 10^9 ohm-cm or tracking and eventual flashover will take place. New insulation usually has a surface resistivity greater than 10^{12} ohm-cm at 23°C and 50 percent relative humidity. This value is much less with higher humidity and temperature. If the surface resistivity is reduced to 10^8 to 10^9 ohm-cm by contamination,

a significant surface leakage current will flow. This will dry out the surface and form a dry band. The dry band will be bridged by a small electrical discharge, since the stress locally will exceed the breakdown stress of air at the air-solid interface. The heat from the discharge will decompose the insulation and form a conducting path on the surface. With time, the paths will propagate, forming a tree, and breakdown eventually follows.[31]

5.3 <u>Basic Theory of Partial Discharges in Cracks and Voids</u>. A microscopic theoretical description of partial discharges is straight-forward and can be readily related to observed phenomena. Expanding this description to the microscopic regime becomes very complicated because voids and cracks vary in shape, smoothness, and composition, and each partial discharge produces chemical products that change the gas composition within the void and also the surface of the crack or void. As a consequence, a set of theoretical models that can usefully predict the effects of partial discharges must be based largely on the manipulation of empirical data derived from tests using circuits such as shown in Figure 28.

5.3.1 <u>Size, Shape, Location, and Distribution of Voids and Cracks</u>. A precise count of the number of cracks and voids is very hard to get, requiring sectioning the sample dielectric and scanning it with a mass spectrograph or similar instrument. Even then, many cracks and voids would be unaccounted for or lost during the dissection process. It is easier to derive the size, shape, and general location of cracks and voids within the part or dielectric medium from non-destructive optical and electrical observations.

Cracks and voids are easily located in transparent and some slightly opaque materials with polarized light and a magnifying glass. Polarized light shining through the dielectric illuminates the cracks and voids, which then appear as skinny lines, curved surfaces, and bulges in the insulation. Slowly rotating the polarizing screen brings out other portions

31) J. H. Mason, "Discharges", IEEE, Trans. on Elec. Insulation, Vol. EI-13, No. 4, August 1978, pp 211-1 238

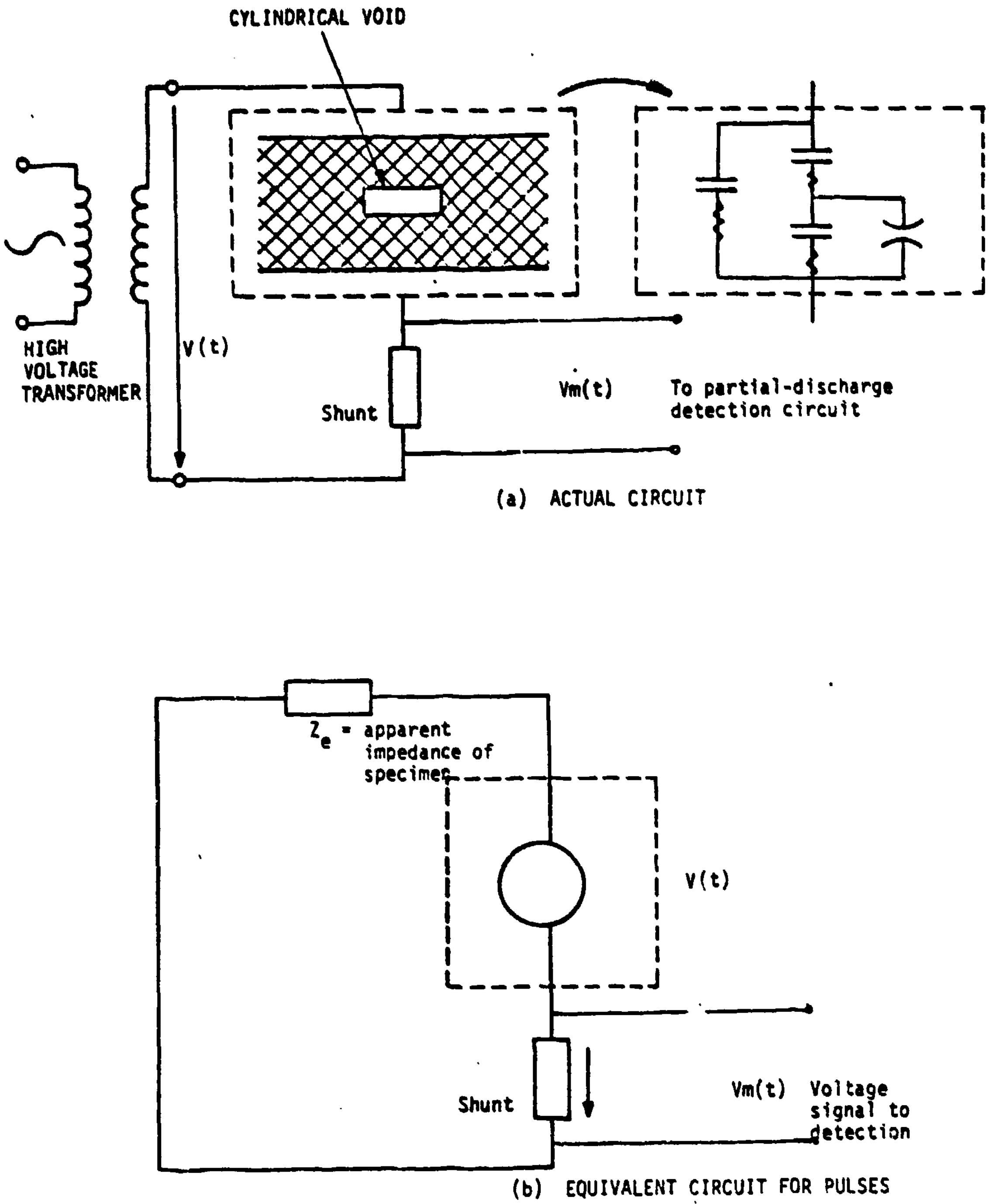


FIGURE 28. TEST CIRCUIT FOR MEASUREMENT OF PARTIAL DISCHARGES

of the cracks and voids. This is a low-cost, effective, and fool-proof method of detection, provided the dielectric is transparent. Only surface cracks and voids can be seen in black and opaque materials, but even these are important to find prior to expensive electrical testing. Interior cracks and voids become evident during electrical testing.

A void in a dielectric is an island having a dielectric constant that differs from that of the dielectric, thus altering the electric field in its vicinity. Shown in Figure 29 are examples of dielectric stress augmentation in void.[32] The following symbols appear in the illustration:

E_o = Voltage stress in the gas (disc)

E_ε = Voltage stress in the dielectric in series with the gas filled void

ε_r = Dielectric constant of the material

E_{om} = Voltage stress in the gas (sphere)

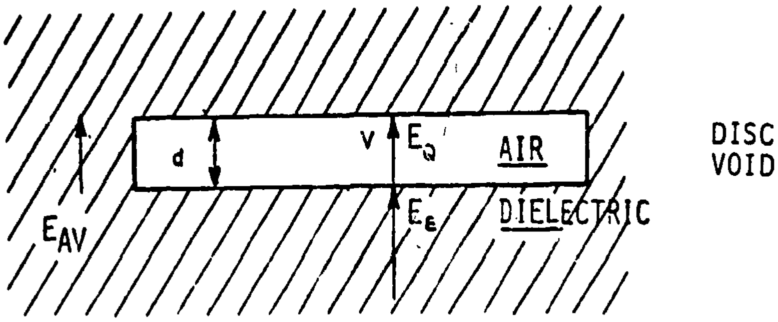
E_{av} = Voltage stress across the solid dielectric

V = Initiation voltage of the void of the void and dielectric

The worst case is that of the disc shaped void shown in cross section on the top of the figure. Here, with a width much greater than d, virtually all of the electric flux intercepted by the area of the disc ($E_o \times E_{av}$ x area) is forced to pass through the void. The stress in the gas dielectric necessary to sustain this flux is seen to be $E_o = k\ E_{av}$ where k is the dielectric constant of the dielectric material.

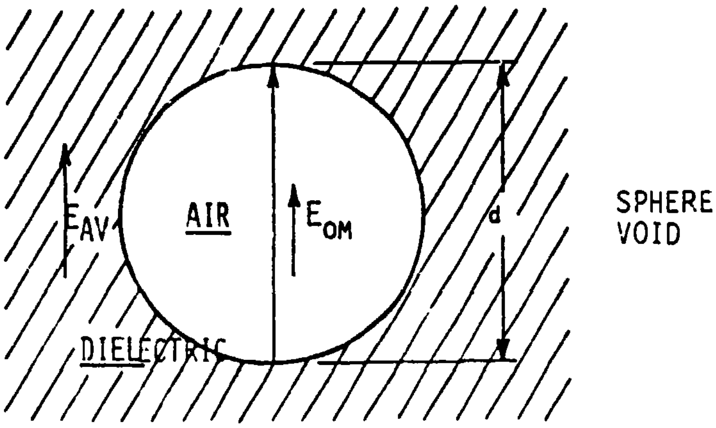
A spherical void is shown in cross section on the bottom of Figure 29. Here, part of the average flux in the solid insulation skirts the void while the remainder passes through the void. The effect, however, is such that the maximum stress, E_{om}, always exceeds the average stress, E_{av}, as given by the formula in the figure. A value for polyethylene is shown. If the dielectric constant of the material is increased the field augmentation will increase proportionally for the disc type void, but for the

32) P.F. Bruins, Plastics for Electrical Insulation, Interscience Publishers, N.Y.,N.Y. 1968, pp 25-58.



$$E_0 = \varepsilon_r E_\varepsilon = 2.25\ E_\varepsilon$$

$E_0 > 70$ V/MIL $\quad V > 300$



$$E_{OM} = \frac{3\varepsilon}{1 + 2\varepsilon} E_{AV}$$

$$= 1.23\ E_{AV} \text{ (POLYETHYLENE)}$$

FIGURE 29. STRESS INCREASE IN VOIDS

spherical void it is seen to approach a maximum value of 1.5 E_{av}. A low dielectric constant insulation will minimize the effect of voids.

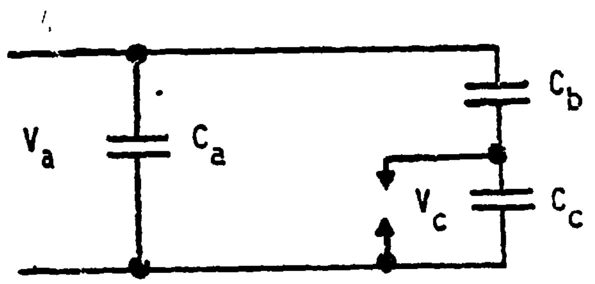
The effect of void size will now be considered. The capacitance of a small disc shaped void is

$$C_0 = \frac{K\varepsilon_0 A}{d}$$

Where k is the dielectric constant of the enclosed media (gas = 1.0), A is the area of the disc in square meters, d is the separation between the faces of the disc in meters, and ε_0 is the permittivity of evacuated space, 8.885×10^{-12} farad per meter. The value C_c is important because it can be used in calculating the magnitude and energy of a pulse during a partial discharge in the void.

What happens when C_c discharges was analyzed by J.H. Mason[33]. The small capacitor C_c in the circuit shown in the sketch is instantaneously short-circuited. The consequent charge transfer is:

$$Q_c = \left(C_c + \frac{C_a C_b}{C_a + C_b}\right)\Delta V_c = \Delta V_c\left(\frac{C_a C_c + C_b C_c + C_a C_b}{C_a + C_b}\right) \qquad (3\text{-}12)$$



Where:

V_a = applied voltage

V_c = voltage across the void

C_a = capacitance of the total dielectric less that of the void and C_b

C_b = capacitance of dielectric in series with the void

C_c = capacitance of the void

Q_a = apparent discharge magnitude detected at the terminals, picocouloumbs

Q_c = discharge magnitude in the void, picocouloumbs

Simultaneously, a voltage pulse, which is effectively a step voltage (δV_a) having a risetime of between 10 and 100 nsec, is generated at the terminals of the insulation:

33) J. H. Mason, "Discharge Detection and Measurements," Proceedings of IEEE, Vol. 112, No. 7, July 1965, p 1407.

$$V_a = \Delta V_c \left(\frac{C_b}{C_a + C_b} \right) \quad (3\text{-}13)$$

The apparent discharge magnitude, observed at the terminals, is:

$$Q_a = \Delta V_a \left(C_a + \frac{C_b C_c}{C_b + C_c} \right) = \Delta V_a \left(\frac{C_a C_b + C_a C_c + C_b C_c}{C_b + C_c} \right) \quad (3\text{-}14)$$

We can simplify the handling of the expression by letting: (3-15)

$$C_3 = C_a C_b + C_a C_c + C_b C_c$$

Usually, a small area of the discharge site is almost completely discharged, so that:

$$\frac{Q_c}{Q_a} = \left(\frac{\Delta V_c}{\Delta V_a} \right) \left(\frac{C_3}{C_a + C_b} \right) \left(\frac{C_b + C_c}{C_3} \right) \left(\frac{\Delta V_a}{\Delta V_c} \right) \left(\frac{C_a + C_b}{C_b} \right) \quad (3\text{-}16)$$

$$\doteq 1 + \frac{C_c}{C_b} \quad (3\text{-}17)$$

Most of the charge is released from the region where $\Delta V_c \rightarrow V_c$, so the energy liberated will be:

$$W = 1/2\, Q_c V_c = 1/2\, Q_a \left(1 + \frac{C_c}{C_b} \right) V_i \left(\frac{1}{1 + \frac{C_c}{C_b}} \right) = 1/2\, Q_a V_i \quad (3\text{-}18)$$

where:

W = energy in nanojoules

V_i = applied voltage in kilovolts peak

Q_a = charge in picocoulombs

Thus, we have a method of calculating the voltage, charge, and energy of a partial discharge in a void for a given applied voltage from the dimensions of the void and the dielectric constant of the surrounding dielectric.

A method of handling the distribution of voids was recently developed by S. Herabayashi, Y. Shebuya. T. Hasegawa, and T. Inuishi.[34] First they analyzed a single void for initiating voltage V_s and charge Q caused by partial discharges. Then the "void distribution function" M(d,s) was defined, with s the discharge area and d the gap spacing, assuming that many voids exist within the insulation whose gap spacings and discharge areas are d~d+dt and s~s+ds respectively. The total number of voids (N_t) can then be described by the expression:

$$N_t = \int_0^{\infty}\int_0^{\infty} M^* (V_s,Q)dV_s dQ \qquad (3\text{-}19)$$

Where M^* = is another void distribution function.

The number of partial discharges whose charge is $(Q_j - \Delta Q/2) < Q < (Q_j + \Delta Q/2)$ during a half cycle at ac voltage will be determined for each half cycle using a pulse height analyzer or similar recording device, giving the value N_{ij} which corresponds to $N(V_i Q_j)$. This expression can be then reformed to a reference equation as follows:

$$M^*(V_i,Q_j) = \frac{N_{i+1}^{j} - N_{i-1}^{j}}{V_{i+1} - V_{i-1}} - \frac{2}{V_i} N_{ij} + \frac{2}{V_i^2}\sum_{k=1}^{i} N_{kj}\left(\frac{V_{k+1} - V_{k-1}}{2}\right) \qquad (3\text{-}20)$$

With this analysis tool, several types of partial discharges and other phenomena can be distinguished in test data. These phenomena include loose contacts (pulse at 0 voltage level) creepage paths (pulses with high magnitude at peak voltage and zero magnitude at zero voltage), small voids (single spikes), and partial discharges which have multiple spikes.

5.3.2 Material Dielectric Constant and Conductivity. The previous equation,

34) S. Hirabayashi, et al., "Estimation of the Size of Voids in Coil Insulation of Rotating Machine," IEEE Transactions on Electrical Insulation, Vol. EI-9, No. 4, Dec. 1974, pp 129-136.

$$Q_c = \Delta V_c \frac{C_aC_c+C_bC_c+C_aC_b}{C_a + C_b} \qquad (3\text{-}21)$$

indicates that for a given charge transfer, V_c depends upon the capacitances C_a, C_b and C_c. Since capacitance is $C = k\epsilon_0 \frac{A}{d}$, each capacitance depends upon the dielectric constant. The lowest voltage across the void will occur with short gap spacing d, and low dielectric constant. As the dielectric constant is increased the field stress across the void increases, resulting in more and bigger partial discharges.

Insulating materials have very high volume resistivity, so conductivity has negligible effect on partial discharges initiated by ac voltages, conductivity is significant when a dc voltage is applied. The dc-circuit analog of the above equation is obtained by substituting for

C_a a fixed resistor of value R_a.
C_b a resistance of higher value R_b.
C_c a resistance of infinite value, or C_c.

Applying a dc voltage across very high resistivity dielectric produces these effects: (1) the initial distribution of the dc potential across the dielectric is related to the capacitance of its components, (2) in time, this distribution changes to relate to the resistivities of the components of the dielectric, (3) initial space charges within voids dissipate, allowing partial discharges to occur, breakdown voltage of the contained gas is exceeded, and (4) the discharge initiation and extinction voltages across the void depend upon the temperature, increasing as temperature decreases. For pure dc the discharge rate R is:[35]

$$R = \begin{bmatrix} 0 & E_c < E_d \\ E\sigma/E_d k & E_c \geq E_d \end{bmatrix} \qquad (3\text{-}22)$$

where:
E = voltage across the dielectric
E_c = voltage across the void
E_d = initiation voltage for the gas filled void
σ = bulk conductivity of the insulation

35) H. Feibus, "Corona In Solid-Insulation Systems," IEEE Transactions on Electrical Insulation, Vol. EI-5, No. 3, September 1970, pp. 72-78.

5.3.3 Gas Pressure and Composition. Prior to flight, the voids and cracks within unpressurized electrical insulation are at near Earth sea-level ambient pressure. In flight, the ambient pressure falls, and the pressure inside the voids decreases very slowly. In the meantime, the materials surrounding the void are backfilling the void with their outgassing, which may contain hydrogen, hydrocarbons, or halogens (flourides). Some of these gases, particularly hydrogen and some hydrocarbons, have low breakdown voltage (Figure 6).

Model voids used to evaluate insulations usually have gap thicknesses (dimension d) of 0.025 to 0.25 mm, which are representative of values found in practice.[34] Voids as small as 0.005mm were measured in oil-filled paper capacitors. They were in unimpregnated paper and between films and electrodes. These voids caused multiple failures, so the capacitors had to be redesigned to eliminate the voids. In those same capacitors, which had been designed for terrestrial use, the voids were found to be filled with a mixture of hydrogen and hydrocarbons from the oil and paper.[36]

If the size of the void is known, then the Paschen-law curve can be used in calculating the voltage at which partial discharges will initiate. For example, with hydrogen the pressure-times-spacing-factor is:

Pressure 1×10^5 N/m^2 at Earth ambient
Distance 2.5×10^{-3} cm
Pxd = 250 pa-Cm
Pa = N/m^2

The voltage at which discharges will initiate across the void can then be obtained from Figure 6. For example, for hydrogen, V_c would be 300 volts.

Conversely, if the applied voltage at which partial discharges occur is known, the above equations can be used to test for the presence of

36) B. Ganger, and G. Maier, "On Electrical Aging of Oil-Impregnated High-Voltage Dielectrics," IEEE, Transactions on Electrical Insulation, Vol. EI-9, No. 3, Sept. 1973, pp 92-97.

hydrogen.

The field strength within the void or crack will decrease with time as shown by K. Kikuchi, K. Ninomiya, and H. Miyauchi.[37] They also found that the dc breakdown strength of cross-linked polyethylene decreased with increased pressure. A fifty percent decrease in breakdown strength was measured for a temperature increase of 45°C using thin sheets (0.1mm) without cable impregnating additives. Thicker sheets (1.0mm) with and without additives had less than 35 percent decrease in breakdown strength.

5.3.4 Surface Surrounding Void. Initially the void or crack surfaces will be reasonably smooth, macroscopically, in encapsulating materials such as epoxies and polyurethanes. Microscopically the surfaces are always rough with caves and jagged protrusions just as are the surfaces of metallic electrodes.

As the void or crack is exposed to partial discharges, the surfaces will be either erroded (silicones) or treeing will take place (epoxies). The treeing tends to go toward the point of high voltage. Both treeing and erosion will make the void bigger, increasing the number and magnitude of the discharges and eventually lead to breakdown of the dielectric.

5.3.5 Temperature Effects. Much useful information concerning molecular structure can be derived by analyzing how the anomalous dispersion is shifted with frequency and temperature. For practical insulation materials, substantial changes in dielectric properties occur at high temperature (Figures 25 and 26). At room temperatures and low frequency, dielectric loss is low and changes but slightly as temperature is increased. On further heating, the viscosity of the polymer is decreased until polar groups can move under the forces supplied by the external field. At some temperature, polarization and relaxation will be in equilibrium with the applied field at all times during a cycle. In such a

37) K. Kikuchi, et al., "Characteristics of DC Dielectric Breakdown of Plastic Insulation," Conference on Electrical Insulation and Dielectric Phenomena, 1973 Annual Conference, Nat. Academy of Sci., pp 327-332.

high temperature regime, dielectric loss increases very rapidly with temperature. The loss-temperature curve rises continuously and the polymer at high temperatures becomes a semiconductor (Figure 27).

Significant changes in the dielectric constant also occur with change in temperature (Figure 25), altering the parallel and series capacitances surrounding an enclosed void or crack. Lowering the dielectric constants lowers the impressed voltage across the void. The partial discharge initiation voltage would then rise if gas density were held constant inside the void. The density of a gas is a function of temperature and pressure. The gas density is defined as the number of molecules per cubic centimeter at pressure P. Pressure, volume, and temperature of a perfect gas are related by the equation: PV = NRT.

where: P = pressure in torr
V = volume in cubic centimeters
T = absolute temperature in degrees Kelvin
N = number of moles
R = Joules per degree Celcius per mole

As gas density is increased from standard temperature and pressure, the partial discharge initiation voltage is increased because at higher densities the molecules are packed closer, and a higher electric field is required to accelerate the electrons to ionizing energy within the mean free path. The partial discharge initiation voltage decreases as gas density is decreased from standard pressure and temperature because the longer mean free path permits the electrons to gain more energy prior to collision. As density is further reduced, a minimum initiation voltage is eventually reached. The pressure corresponding to minimum initiation voltage depends on the gap spacing. A representative minimum initiation voltage for air is 326 volts dc.

With a further reduction in density, the initiation voltage rises steeply because the spacing between gas molecules becomes so great that although every electron collision produces ionization, it is hard to achieve enough ionizations to sustain the chain reaction. Finally, the pressure becomes so low that the average electron travels from one

electrode to the other without colliding with a molecule. This is the reason why the minimum initiation voltage varies with spacing--as the spacing is decreased the minimum initiation voltage occurs at lower voltage at constant pressure, as shown by the Paschen-Law Curve (Figure 30).

The test conditions for simulating a given operating pressure and temperature can be calculated by using this relationship derived from the ideal gas law:

$$P_t = P_o \left[\frac{273 + t_t}{273 + t_o}\right] \text{ (Volume being constant)} \qquad (3\text{-}24)$$

where: t_o = operating temperature in degrees Celcius
t_t = test temperature in degrees Celcius (usually room temperature)
P_o = operating pressure in N/m^2
P_t = test-chamber pressure in N/m^2

5.3.6 Impressed Voltage. Partial discharges are counted with a pulse height analyzer or similar instrument when dc measurements are conducted. The random nature of the discharges make quantitive measurements difficult, especially with capacitors for which most test apparatus is designed to evaluate a 10 picofarad capacitor. With a large capacitor, say 1.0 mfd. a small reading of 10 picocoulombs may represent an actual 100 picocoulomb discharge inside the capacitor void--a very damaging discharge. With transformers, circuit boards, and inductors the readings are realistic. Kreuger[38] has shown that the ratio of charge transferred in a dielectric void to the change in charge observed in the external circuit (R_{ct}) is:

$$R_{ct} = \frac{\text{charge transfer in the void}}{\text{charge in the external pulse}} = 1 + \frac{t}{kd} \qquad (3\text{-}25)$$

where: d is the thickness of the cavity
t is the thickness of the dielectric
k is the dielectric constant of the solid material

38, F. H. Kreuger, Discharge Detection in High Voltage Equipment, Elsevier, 1964

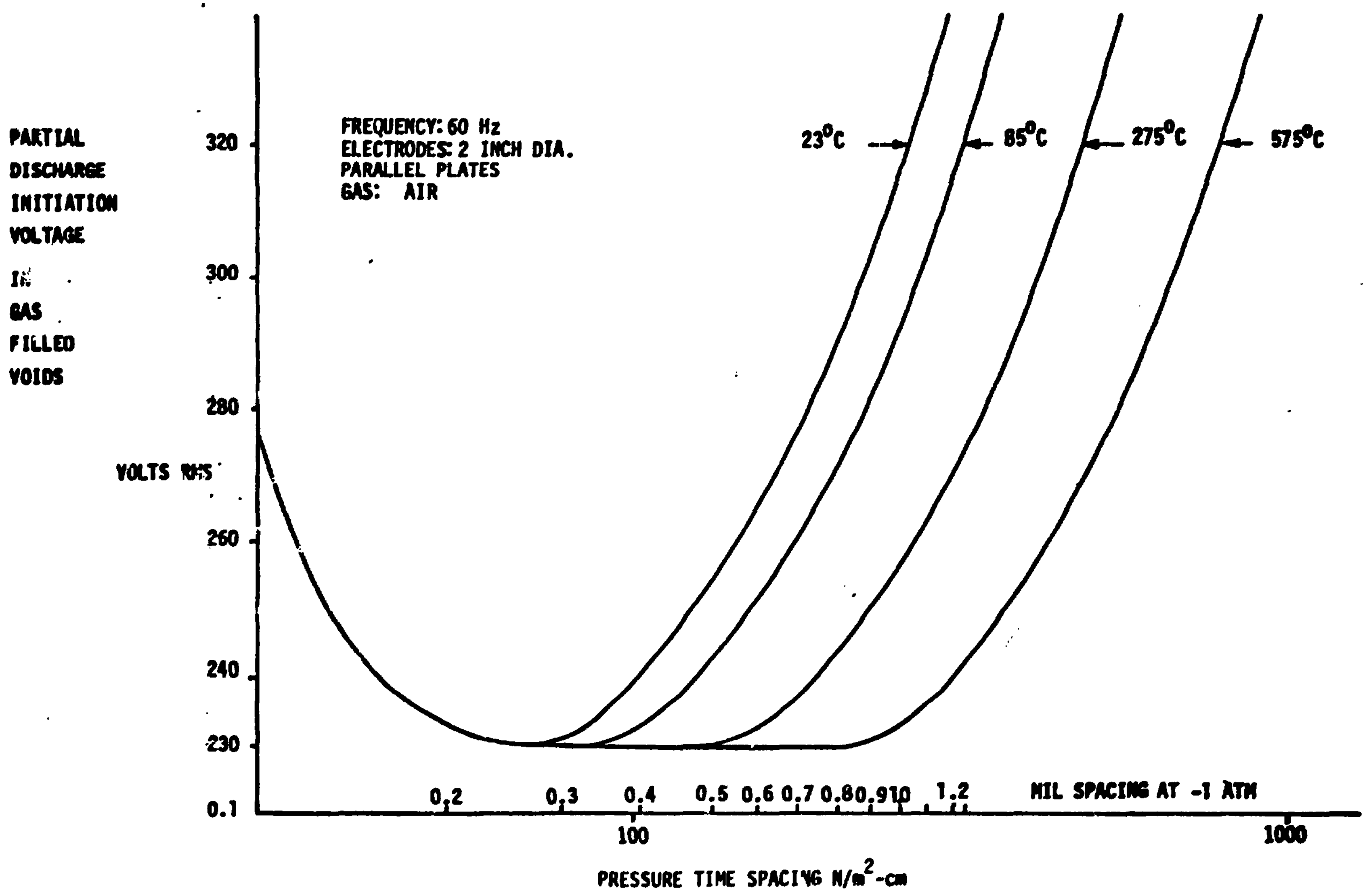


FIGURE 30. PRESSURE TIMES SPACING AS A FUNCTION OF TEMPERATURE

For example: if a void in a dielectric has these features:

$t = 0.017$

$k = 3.4$

$d = 0.001$

then:

$$R_{ct} = \left(1 + \frac{t}{kd}\right) = \left(1 + \frac{0.017}{3.4 \times 0.001}\right) = 6$$

Thus, a 10 pc reading on a corona detection instrument would present a 60 pc discharge in the capacitor. A 60 pc discharge would damage a typical capacitor.

Time is important when measuring partial discharges with direct voltage. Measurements by Mason[31] have been shown that cavities of 2 mm diameter cavity may take as long as 10^3 sec to discharge at a given steady-state voltage. For smaller cavities of 0.4 mm diameter, the time log was up to 10^4 sec. In tests with epoxy resin impregnated paper at 20°C, the initiation voltage, V_i, was up to 3.5 times greater when the voltage was raised rapidly rather than with step of 20 sec duration, but the time effects were small for samples tested at 60°C. Temperature is very important when measuring partial discharges.

Ionization occurs in the gas and a charge accumulates on the surfaces of the cavity, which enhances the stress in the gas during voltage rise (fall). Then if the voltage is raised in small steps every 20 sec, the initiation voltage will be much lower than found with rapidly rising voltage.

When alternating voltage is applied to discs containing a cylindrical cavity, as in Figure 29 (upper), the inception voltage is within $\pm 15\%$ of the voltage predicted by the formula $V_i = E_o \left[d + (t - d)/\varepsilon_s\right]$ where t is the thickness of the sample under test, including the void and ε_s depends upon the relative permittivity ε_r and the geometry and orientation fo the cavity where

$\varepsilon_s = \varepsilon_r$ for pancake shaped voids horizontal to the electrodes

$\varepsilon_s = 1$ for pancake shaped voids perpendicular to the electrodes

$\varepsilon_s = \frac{3\varepsilon_r}{2 + 2\varepsilon_r}$ for a spherical shaped void within the test sample

A rule to follow when comparing alternating voltage to direct voltage readings is to

consider peak-to-peak voltage. With direct voltage all the voltage is impressed across the dielectric and void in one direction. With alternating voltage the voltage impressed across the dielectric and void is from the positive peak to the negative peak of the sine wave.

With 60-Hz ac voltages, the partial discharge counts increase significantly as applied voltage is raised above the initiation voltage. With ac superimposed upon a dc voltage, the partial discharge pulses decrease in both magnitude and number as the ratio of dc voltage to ac voltage, peak increases from 0.05 to 1.0. The loss tangent of the material also decreases significantly (Figure 31).

Raising the frequency of ac reduces the voltage at which partial discharge initiates, as shown in Figure 32 for spacecraft epoxies. The initiation voltage is relatively constant for frequencies up to 2 kHz. Above 2 kHz there is a significant decrease. Much of this decrease can be attributed to the gaseous breakdown within voids, a prime contributor to the partial discharges.

The effect of a square wave is similar to that of adding an impulse to an ac voltage. R. J. Densley[39] developed the technique of analyzing square waves. He found that the leading edge of a square wave will have the same effect as an ac voltage with an impulse at the zero voltage point on the sine wave. The impulse from the square wave will initiate partial discharges which may continue throughout the waveform. Most of the discharges occur immediately after the impulse with few or none at the end of the constant voltage plateau. The quantity of the discharges and their duration depends upon the amplitude of the square wave, the reverse stress across the void or crack after the leading edge passes, and the frequency of the square waves.

39) R. J. Densely, "Partial Discharges in Electrical Insulation Under Combined Alternating and Impulse Stresses", IEEE Transactions on Electrical Insulation, Vol. EI-5, No. 4, December 1970, pp. 9[illegible]3.

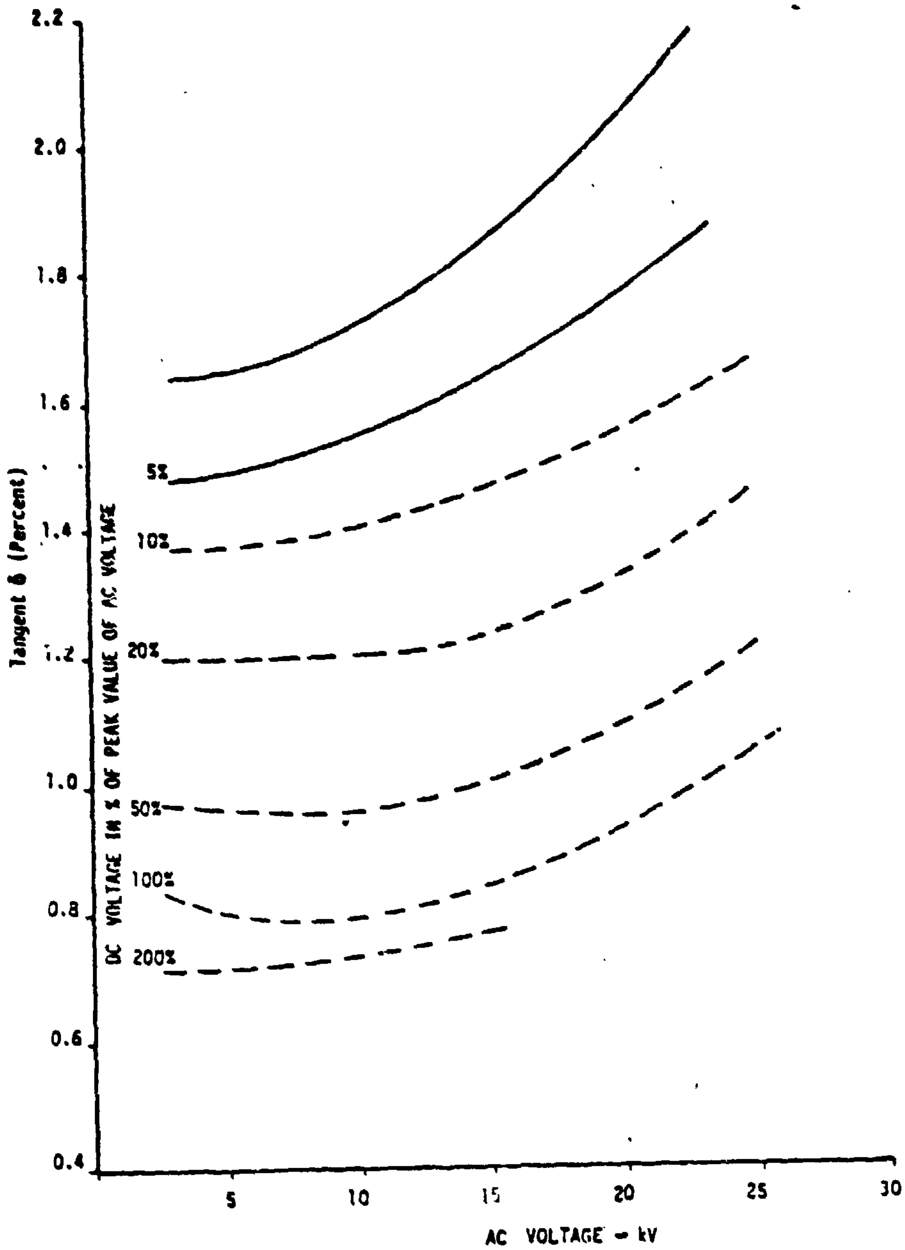


FIGURE 31. DEPENDENCE OF TAN δ ON THE AC VOLTAGE WITH SIMULTANEOUS DC VOLTAGE. IMPREGNATED PAPER CABLE INSULATION. 96.0°C, 50 Hz.

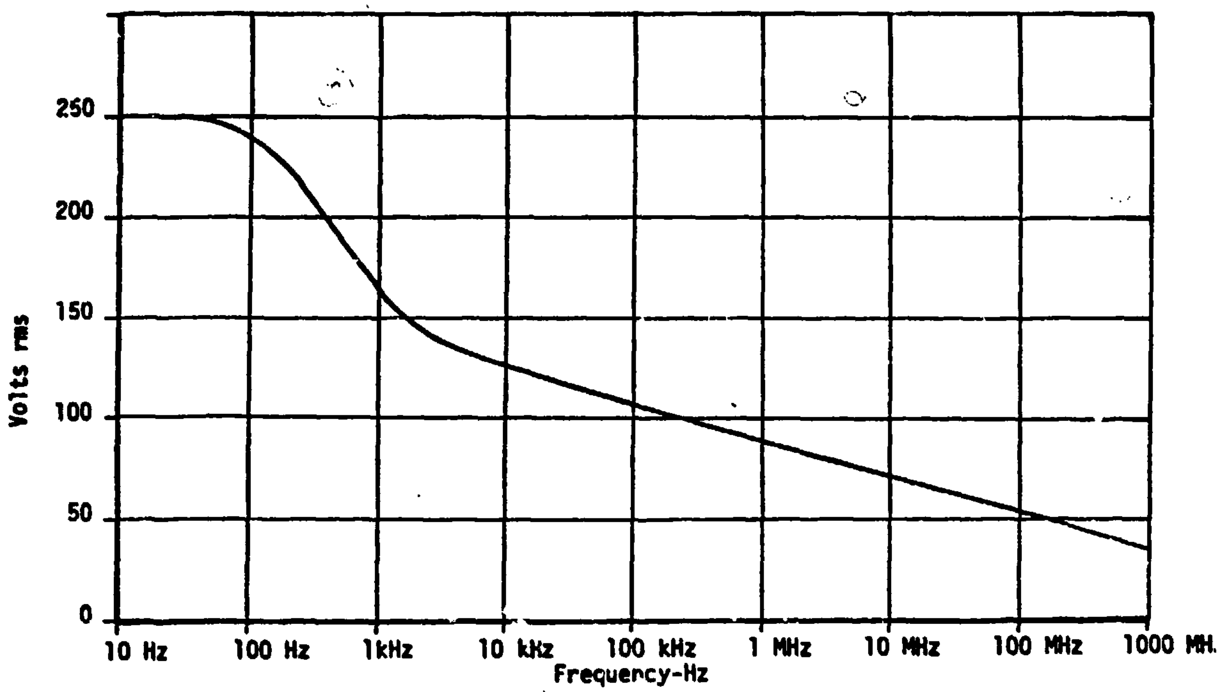


FIGURE 32. LOWER BREAKDOWN VOLTAGE RESULTS FROM HIGHER FREQUENCY BETWEEN THIN-FILM COATED PARALLEL PLATES

5.4 Surface Effects. In this section. the term "flashover" means that the surface of a solid insulator has become so conductive that it can sustain the flow of substantial current from one high-voltage electrode to the other. Elsewhere in this manual, the term "flashover" also refers to the breakdown of a gas dielectric.

Current flowing across a surface of an insulator, especially when slightly wetted and containing a conductive contaminant, may produce enough heat to generate a track of carbon, which becomes a conductive path tending to reduce the capability of the insulator to resist the voltage. With some materials, the surface erodes, but no "track" is produced. Fillers effectively reduce the tracking tendency of organic materials. Eroding materials. such as acrylics do not require filler protection. Obviously, no tracking is the ideal requirement for an organic insulator. Tracking can also be controlled by reducing the volts per millimeter stress on the surface. Petticoat insulation configurations lengthen the surface creepage path to

reduce stresses tending to cause tracking.

When new, cycloaliphatic epoxy with inorganic filler is applied to the surface of a laminate, the finished product can withstand higher voltage stress than porcelain. Surface erosion and exposure to ultra violet radiation will degrade the epoxy to where it is inferior to the porcelain. In one application having a glass-cloth epoxy-based laminate coated with cycloaliphatic epoxy, the surface was stressed at a voltage of over 45kV/cm impulse and 35kV/cm dc. However, the atmosphere was sulfur hexafluoride atmosphere, and such a high voltage-stress is not recommended for long life equipment.

The flashover voltage was measured between 1.9-centimeter diameter washers on an uncoated glass epoxy-band laminate (Figure 33). The washer was spaced one to four centimeters apart. Shown in Figure 34 is the flashover voltage initiation as a function of spacing at three frequencies. The impulse and steady-state flashover voltage stress is shown for the same configuration in Table 9.

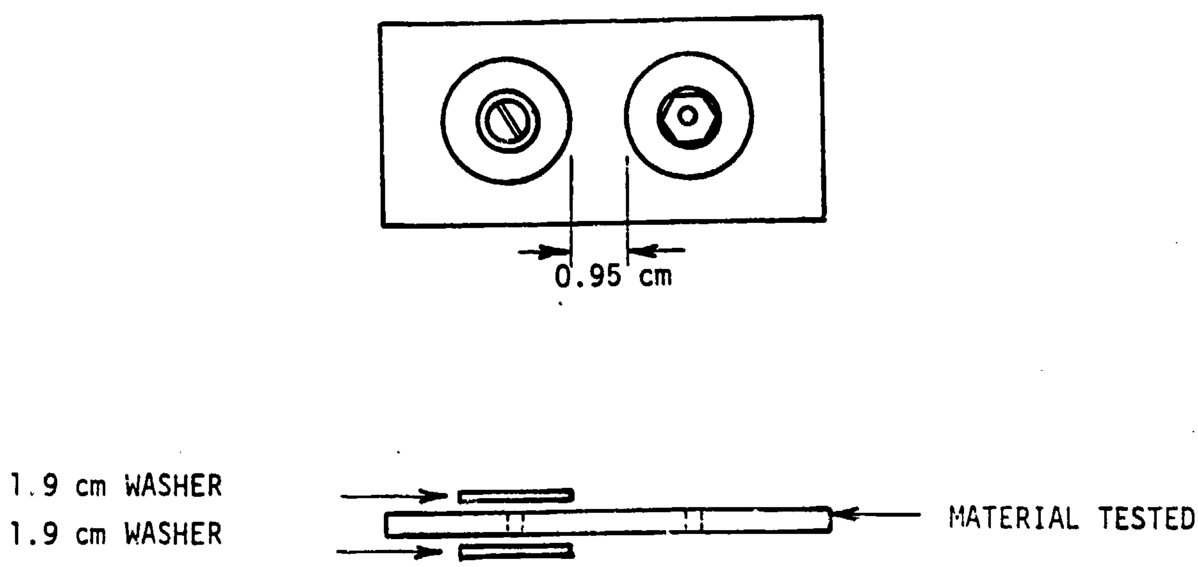


FIGURE 33. FLASHOVER FIXTURE

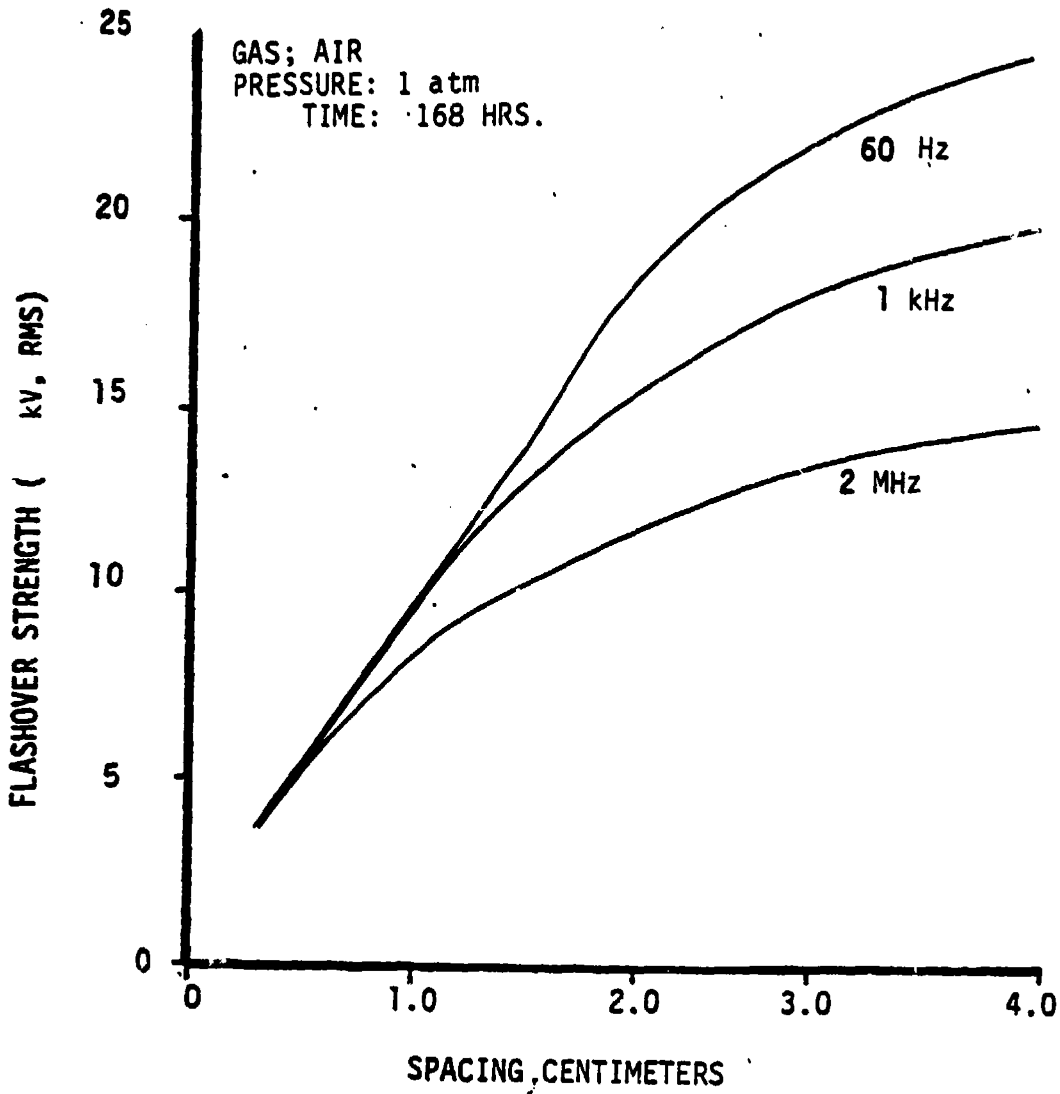


FIGURE 34. EFFECT OF SPACING ON THE INITIAL VALUES OF STRENGTH FOR THE FIXTURE SHOWN IN FIGURE 33

5.4.1 Effect of Temperature On Flashover Strength. It is both interesting and useful to determine the relationship between flashover strength at 25°C and that which would prevail at some other temperature, T. For gaseous breakdown in a uniform field, this relationship involves the ratio of the gas densities at the two temperatures. In order to test this relationship, it is only necessary to multiply the 25°C value by the factor $(25 + 273)/(T + 273)$, which is the inverse ratio of the absolute temperatures involved. This ratio is part of the well-known air density correction factor, which is the commonly used in spark-gap measurements over a considerable range of density and gap

TABLE 9

COMPARISON OF STEADY-STATE AND IMPULSE FLASHOVER STRESS,

V/CM (PEAK) FOR GLASS EPOXY-BOND LAMINATES

Test (1 Minute Duration)	Average Flashover Strength For 1-CM Spacing kV
Steady-State	
60Hz	14.1
dc positive	14.9
dc negative	16.7
Pulse	
positive	17.1
negative	18.6

length. The broken lines in Figure 35 show the values which are obtained when this factor is applied to the 25C flashover values.

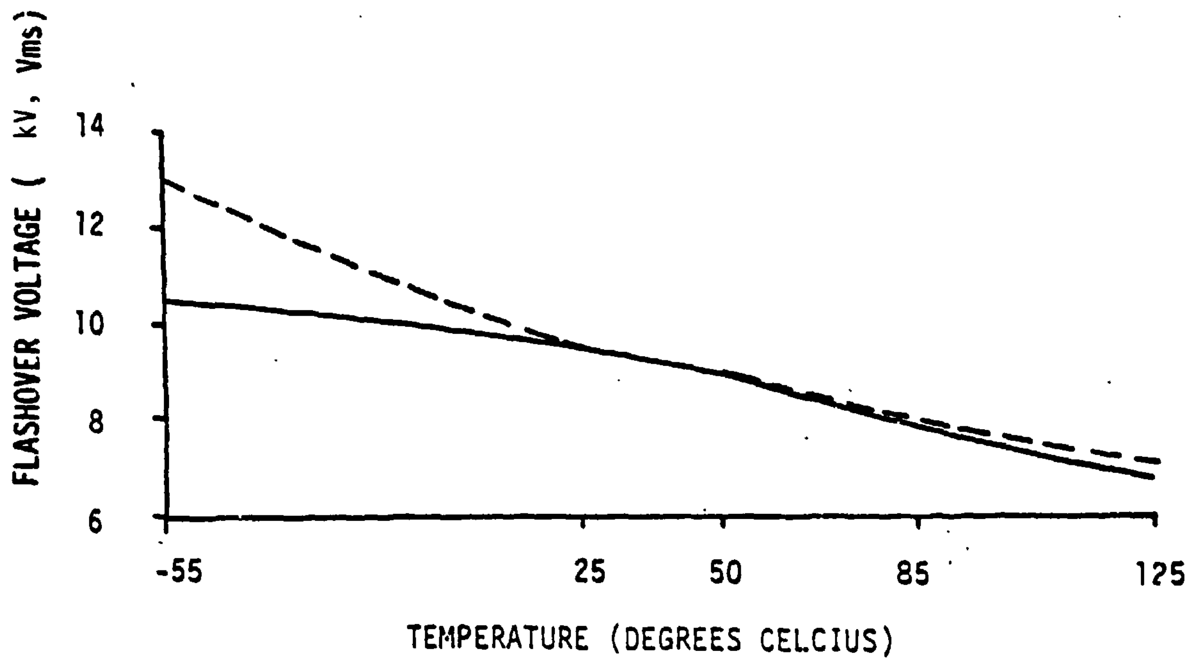


FIGURE 35. EFFECT OF TEMPERATURE ON 60 Hz FLASHOVER STRESS

5.4.2 Other Effects. All materials have lower flashover strength at higher frequencies. The example in Figure 36 illustrates the magnitude of change.

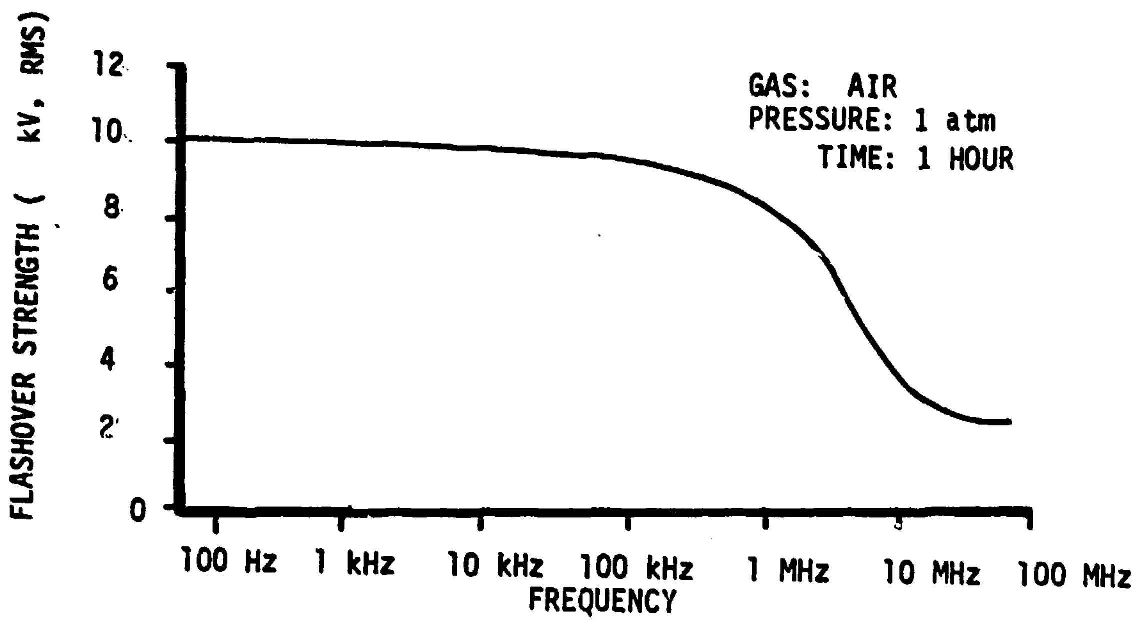


FIGURE 36. EFFECT OF FREQUENCY ON FLASHOVER STRENGTH FOR CONFIGURATION SHOWN IN FIGURE 33

High dielectric constant materials have much lower resistance to surface voltage creep than the low dielectric constant materials. Figure 37 illustrates the advantage in selecting the correct dielectric constant insulation. The "breakdown factor" in the illustration represents the results of many measurements showing how a decreasing flashover voltage can be expected across dielectric when insulations with progressively higher dielectric constants are tested.

A bibliography on surface flashover, surface creepage, and tracking on or within solid insulation is cited in References 40 through 57.

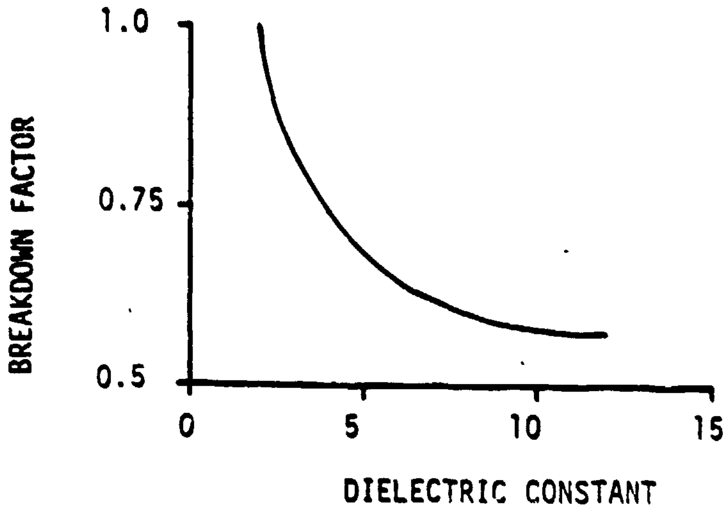


FIGURE 37: VARIATION OF FLASHOVER VOLTAGE WITH CHANGING INSULATION DIELECTRIC CONSTANT

40) G. Alex, (FIMAG Finsterwalde, East Germany): "Tracking Resistance of 1-v Insulating Materials," (Beltrag zur Festigkeit von Isolierstoffen des Niederspannungsbereichs gegen Kriechstoeme), Elektrie, Vol. 23, No. 9, p 364-6, Sept. 1969. IEEE Trans.Elect.Insul., Vol. EI-1, No. 1, March 1965.

41) N. M. Bashara, F. M. Green and D. Lederer, "Pulse Height and Temporal Distribution at Dielectric Surfaces under Corona," IEEE, Trans. Electrical Insulation, Vol. EI-1, No. 1, pp. 12-18, March 1955.

42) M. V. Billings, and K. W. Humphreys, "An Outdoor Tracking and Erosion Test of Some Epoxy Resins," IEEE, Trans. on Electrical Insulation, EI-3, No. 3, August 1968, p. 62-70.

43) M. J. Billings, A. Smith, and R. Wilkins, "Tracking in Polymeric Insulation," IEEE, Transactions on Electrical Insulation, Vol. EI-2, No. 3, p. 131-6, December 1967.

44) M. J. Billings, L. Warren, and R. Wilkins, "Thermal Erosion of Electrical Insulation Materials," IEEE, Trans. on Electrical Insulation, Vol. EI-6, No. 2, June 1971, p. 82-90.

45) J. J. Chapman, L. J. Frisco and J. S. Smith, "Dielectric Failure of Volume and Surface Types," AIEE Transactions, Communications, & Electronics, Vol. 74, Pt. I, p. 349-356, July 1955.

46) A. V. Dmitriev and Chien-Chien Chiang, "Changes in the Properties of Dielectric Surfaces Under the Effects of a Gas Discharge," Zh. Takhn Fix. 36, (In Russian); English Translation: Soviet Phys.-Tech. Phys. 11, p. 547-551, 1966.

47) T. A. Dakin and G. A. Mullen, "Continuous Recording of Outdoor Insulator Surface Conductance," IEEE, Transactions on Electrical Insulation, EI-7, No. 4, December 1972, p. 169-175.

48) L. J. Frisco, "The Flashover Strength of Solid Dielectrics," AIEE Transactions on Power Apparatus & Systems, Vol. 75, Pt. III, p. 77-83 April 1956.

49) Mo. Kurts, "Comparison of Tracking Test Methods," IEEE, Transactions on Electrical Insulation, Vol. EI-6, No. 2, June 1972, p. 76-81.

50) J. H. Mason, "The Resistance of Sheet Insulation on Surface Discharges," Proc. Institute of Electrical Engineers, Vol. 107A, P. 551-568, Dec. 1960.

51) M. Olyphant, "Arc Resistance," Pt. 1, "Tracking Processes in Thermosetting Materials," Am. Soc. Testing Materials, Bull. 181, p.60-67, April 1952.

52) M. Olyphant, "Arc Resistance," Pt. 2, "Effect of Testing Conditions on Tracking Properties of Thermosetting Materials," Am. Soc. Testing Materials, Bull. 185, p. 31-38, October 1952.

53) T. Orbeck and R. G. Niemi, "Study of Surface Leakage Current and "Dry-Band-Arcing" on Synthetic Insulation Materials and Porcelain Under Wet High Voltage Conditions," Conference on Electrical Insulation and Dielectric Phenomena, 1973 Annual Report, p. 43-50.

54) Y. Toriyama, H. Okamoto and M. Kanazashi (Musashi Inst. Technology, Tokyo, Japan), "Breakdown of Insulating Materials by Surface Discharge," IEEE Transactions on Electrical Insulation, Vol. EI-6, No. 3, p. 124-9, September 1971.

55) C. F. Wallace and C. A. Bailey, "Dip-Track Test," IEEE, Transactions on Electrical Insulation, Vol. EI-2, No. 3, Dec. 1967, p. 137-140.

56) R. Winans, "Safe Minimum Distances for Electrical Creepate and Clearance," Electrical Manufacturing, Vol. 51, No. 1, p. 78-83, January 1953.

57) C. T. Wu and T.C. Cheng "Formation of Clean Zones During the Surface Flashover of Contaminated Surfaces", IEEE, Trans. Elec. Insulation, Vol. EI-13, No. 3, June 1978, pp. 149-156.

5.5 Liquid Dielectrics. Liquid dielectrics may be used as insulators and as a heat transfer medium. Often liquid dielectrics are used in conjunction with solid insulations such as papers, films, and composite materials. By eliminating air or other gases, liquid dielectrics improve dielectric strength of the insulation system. They are also self-healing, in contrast to solid dielectrics, for the affected area of a failure caused by a temporary overvoltage is immediately reinsulated by fluid flow back to it.

Liquids used as insulators are mineral oils, askarels, silicone oils, fluorocarbons (fluorinated liquids), vegetable oils, organic esters including castor oil, and polybutenes (polyhydrocarbon oils).

5.5.1 Selection. In selecting a liquid dielectric, its properties must be evaluated in relation to the application. The most important are dielectric strength, dielectric constant and conductivity, flammability, viscosity, thermal stability, purity, space factor, flash point, chemical stability, and very important--compatibility with other materials of construction and the local atmosphere.

Disadvantages which always accompany the use of liquid dielectrics are cost, weight, and temperature limit. Other disadvantages with many liquids are combustibility, oxidation and contamination, and deterioration of materials in contact with the liquid. Deterioration of materials generates moisture, evolves gas, forms corrosive acids, produces sludge, increases dielectric loss, and decreases dielectric strength.

The selected liquid should provide the best required properties, consistent with keeping disadvantages within the acceptable limits. Typical properties[58] are shown in Table 10.

5.5.2 The Effect of Temperature. The temperature of a liquid dielectric affects its life and stability, as chemical deterioration reactions usually proceed faster at higher temperatures. A pure liquid, in the absence of water or oxygen, would be very stable at rather high temperatures.[59]

Temperature also affects the conductivity of a liquid dielectric.

Table 10 Typical Properties of Dielectric Fluids

Property \ Fluid	Askarel	Mineral oil	Highly saturated paraffin oil	Silicone liquid	Monochlorodiphenyl oxide	Phthalate ester	Isopropyl biphenyl
relative permittivity	4.5-5.8 (25-75°C)	2	2.2	2.7 (23°C)	4.3-4.7 (25-75°C)	4.7-5.5	2.8 (25°C)
dielectric strength kv/.25cm	35	30-35	37	35-40	35	30	60
dissipation factor	.001-.003	.0002-.001 (25°C)	.05 (60Hz)	.0001-.0003	.01 (100Hz)	.0005 (85°C)	.002
volume resistivity ohm-cm	$5x10^{12}$	10^{12}-10^{15}	10^{13}	10^{14}-10^{15}	10^{11} (100Hz)	10^{11}	10^{13}
pour point °C	-14 to -20	-40 to -55	-21	-60	-45	-45 to -52	-55
flash point (COC) °C	166-180	145-154	296	280-320	174	150-220	155
fire point (COC) °C	~320, not clearly defined	150-170	321	310-370	199	240-260	175
boiling point °C	200-350, not well defined	280-370, not well defined	not well defined	not well defined	290-410	230-250	295-305

Note: Values and ranges have been estimated from available published data.

As temperature increases, fluid viscosity decreases and the higher mobility of the ions permits increased conduction[60] (Figure 38). Refining techniques, additives, and blending of liquids are used to thermally upgrade liquid dielectrics.[61 62 63] The normal usable temperature range of liquid dielectric classes is shown in Figure 39.[64]

5.5.3 The Effect of Moisture. Water is soluble to some extent in all insulating liquids. Water usually decreases dielectric strength and increases dielectric loss. Moisture dissolved in pure mineral oil does not affect dielectric strength until it separates from the oil solution and deposits on conductors, solid insulation surfaces, or on solids floating in the oil. However, oil invariably contains suspended fibers, dust, and other contaminates, so the presence of moisture usually lowers the dielectric strength. Polar contaminants dissolved in the oil give moisture its greatest degradation effect on dielectric strength. The effect of moisture varies among the other liquid dielectrics.

58) D. B. Miller, "Tests and Standards to Evaluate the Fire Safety of Electrical Insulating Floids", IEEE Trans. on Elec. Insulation, Vol. EI-13, No. 5, Oct. 1978, pp 378-382.
59) Insulation, Director/Encyclopedia Issue, Lake Publishing Co., Vol. 15, No. 8, June/ July 1969, Copyright 1969.

60) I. Y. Megahed and A. A. Zaky, "Influence of Temperature and Pressure on Conduction Currents in Transformer Oil," IEEE Transactions on Electrical Insulation, Vol. EI-4, No. 4, December, 1969, pp. 99-103.

61) Akira Miyoshi, "A New Additive for Improving the Thermal Aging Characteristics of Kraft Insulating Paper," IEEE Transactions on Electrical Insulation, Vol. EI-10, No. 1, March 1975, pp. 13-17.

62) B. P. Kang, "Thermal Dependency of Viscosity, Power Factor, and Ion Content on Electrical Insulating Oils-II Characteristics of Blended Insulating Oils," IEEE Transactions on Electrical Insulation, Vol. EI-2, No. 1, April 1967, pp. 55-69.

63. E. J. McMahon and J. O. Punderson, "Dissipation Factor of Composite Polymer and Oil-Insulating Structures on Extended Exposure to Simultaneous Thermal and Voltage Stress," IEEE Transactions on Electrical Insulation, Vol. EI-8, No. 3, Sept. 1973, pp. 92-97.

64) F. M. Clark, Insulating Materials for Design and Engineering Practice, John Wiley and Sons, Inc., Copyright 1962.

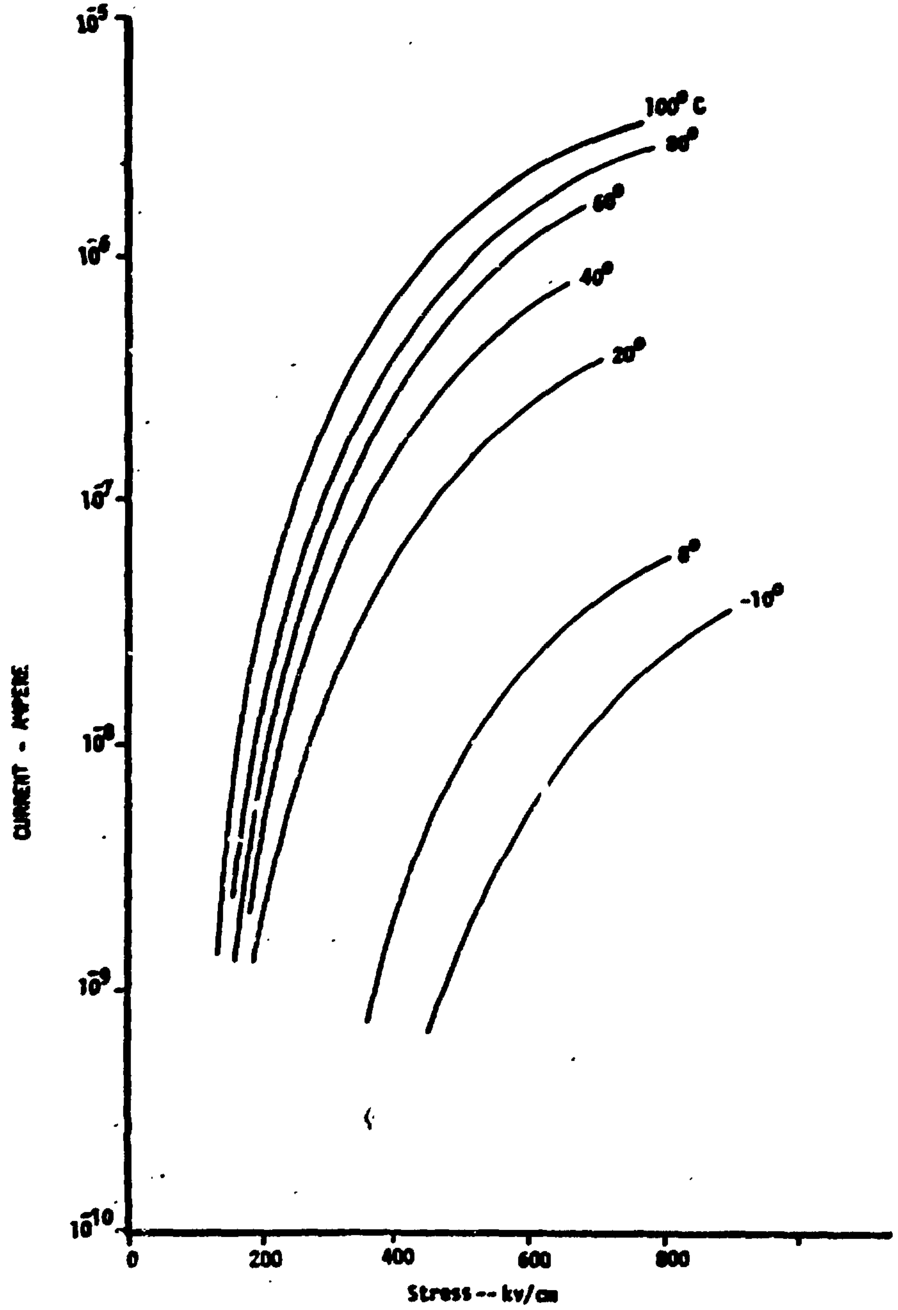


FIGURE 38. EFFECT OF TEMPERATURE ON CONDUCTION CURRENT IN DEGASSED TRANSFORMER OIL

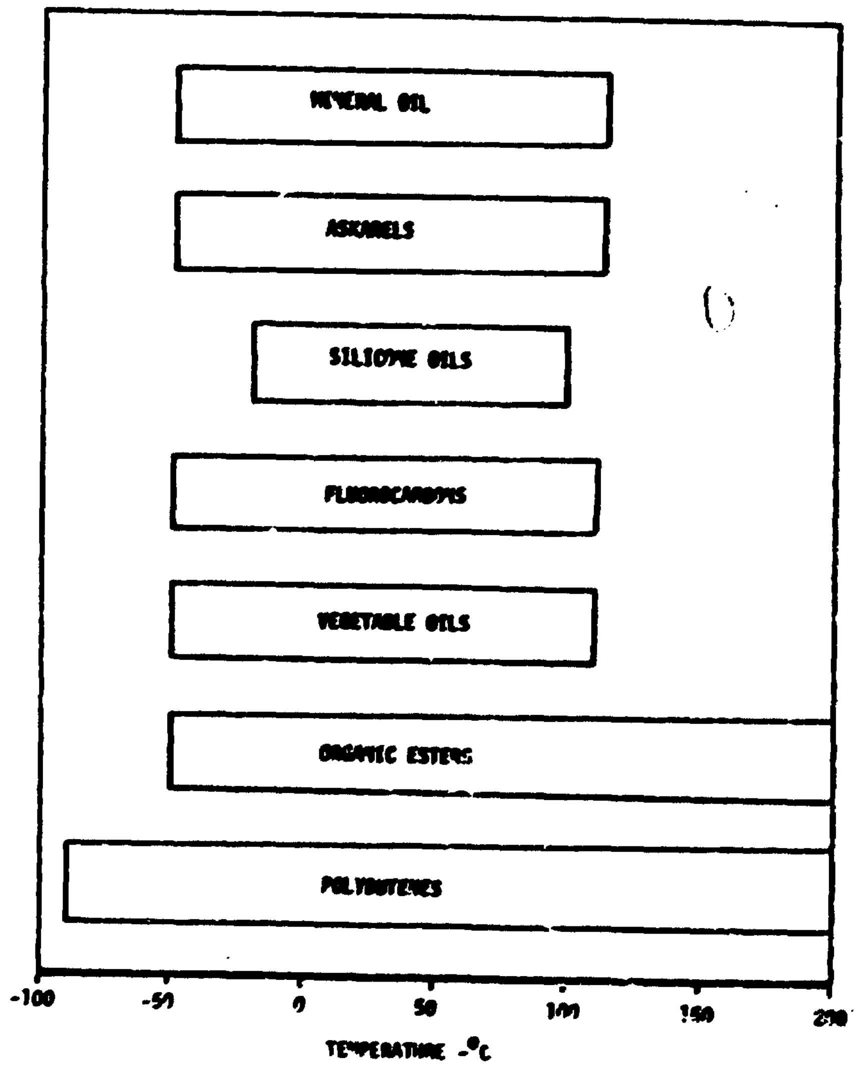


FIGURE 39. NORMAL USABLE TEMPERATURE RANGE OF LIQUID DIELECTRIC CLASSES

In using liquid dielectrics to impregnate cellulosic insulations in transformers, cables, and capacitors, the rate of increase of water solubility in the liquid with increasing temperature is important. When the rate increase in water solubility in the liquid is different from that in the cellulosic insulation, changes in temperature can make the dissolved water separate from the liquid. Such a separation leads to the formation of liquid-water emulsions and severe dielectric degradation.

5.5.4 Dissolved Gas. The effects of gas absorption and liberation in a liquid dielectric must be considered for long term, successful operation.[65] This is especially true when the liquid is used to impregnate solid dielectrics, as in capacitors and cables.

Changes in pressure can make dissolved gases evolve from a liquid. Also, temperature affects the solubility of gas, so heating can cause dissolved gas to evolve from the liquid. Corona will start in the evolved gas bubbles, leading to eventual dielectric breakdown. Thus, liquids used, as impregnates, must have a low, stable gas content.

5.5.5 Breakdown Phenomena. Parameters affecting dielectric breakdown in insulating liquids include electrode materials, electrode surface area and shape, manufacturing treatments, contamination, and deterioration. Birke, Lackey, and Palmer[66] have developed methods of finding the highest stressed liquid volumes between electrodes, enabling them to predict accurately the dielectric breakdown for different electrode configurations.

Manufacturers treat liquid dielectrics in various ways to improve their properties. To obtain the highest initial dielectric values in mineral oil, there is no danger from over-refining. However, over-refining can adversely affect the stability of the oil and it's useful lifetime. The oil must be limited in its aromatic hydrocarbon content, the presence of which decreases the initially high dielectric values of highly refined oil.

65) B. P. Kang, "Stability of Electrical-Insulating Oils," IEEE Transactions on Electrical Insulation, Vol. EI-5, No. 2, June, 1970, pp. 41-46.

66) P. V. Birke, J. Lackey and S. Palmer, "Determination of Highly Stressed Volumes in Oil Dielectrics," IEEE Transactions on Electrical Insulation, Vol. EI-7, No. 3, September, 1972, pp. 139-144.

Liquid dielectrics deteriorate as they are contaminated by sludge, soaps, oxides, and condensation products. These contaminants form faster at higher temperatures and in the presence of reactants, catalysts, nitrogen, sulphur, and acids in the liquid. Ions are found in these contaminates. J.A. Kok[67] theorizes that colloidal ions with high permittivity drift toward the high electrical stress regions where they form chains of dipoles in between the electrodes. Highly stressed regions may be the edges of metal foil electrodes, at paper folds, and where polar contaminates have been absorbed by paper dielectric.

The colloidal dipoles will be separated from each other by a thin layer of oil until they overcome the energy barrier of the oil layers. The act of overcoming the energy barriers, called flocculation, may be aided by the other contaminants. As the chains of dipoles become conducting paths, gas is developed by electrolysis or evaporation. After that ionization and breakdown soon follow. The whole process can occur within a fraction of a second.

5.5.6 Mineral Oil. Mineral oil is the most widely used of all liquid dielectrics. Average characteristics of mineral oil used in common dielectric applications is shown in Table 11.[64] Being a product of crude petroleum, both the source and the refining process affect the end quality of the oil. The refining problem is to remove deleterious materials such as sulphur and nitrogen without removing or destroying the crude-oil constituents that are necessary for long life and stability, such as the aromatic hydrocarbons. Like inhibitors which are added during the manufacture of mineral oil, aromatic hydrocarbons slow down the rate of oxidation (Figure 40).

The contaminate products of oxidation reactions are sludge, asphalt, acids, organic esters, soaps, and oxides. Oil color, as an index of the degree of refinement for unused oils, is also a rough measure of deterioration of oil in service. Cloudiness indicates the presence of moisture, sludge, particles of insulation, products of metal corrosion, or other

67) J. A. Kok, Electrical Breakdown of Insulating Liquids, Interscience Publishers, Inc., Copyright 1961.

TABLE 11

THE AVERAGE CHARACTERISTICS OF MINERAL INSULATING OIL

Property	For Use in Solid Type Cables	For Use in Capacitors and Hollow Core Cables	For Use in Transformers, Switches & Circuit Breakers
Condition	Clear	Clear	Clear
Viscosity	100"(98.9°C)	100" (37.8°C)	58" SSU (37.8°C)
Specific Gravity	.930 (15.5/15.5°C)	.885	.865(15.5/15.5°C)
Color	2.3 (NPA)	1 or less (NPA)	1 or less (NPA)
Neutralization Number	.02(Mg KOH/gram)	.02(Mg KOH/gram)	.02(Mg KOH/gram)
Flash Point (open cup)	235°C	165°C	135°C
Burn Point (open cup)	280°C	185°C	148°C
Pour Point	-5°C	-45°C	-45°C
Free Sulfur	nil	nil	nil
Total (fixed) Sulfur	.35%	.15%	.1%or less
Evaporation (8 hrs/100°C)	.....	.....	8%
Dielectric Strength	30 kv/cm	30 kv/cm	30 kv/cm
Specific Heat (30-35°C)	.....	.412	.4252
Power Factor (100°C)	.001	.001	.001
Chlorides and Sulfates	nil	nil	nil
Resistivity (100°C)	$1\text{-}10 \times 10^{12}$(ohm-cm)	$50\text{-}100 \times 10^{12}$(ohm-cm)	$1\text{-}10 \times 10^{12}$(ohm-cm)
Coef. of Expansion	.00075		.00070
Specific Optical Dispersion	115-120	115-120	110-115
Thermal Conductivity	.....	.....	.39 cal/cm/sec/°C
Refractive Index (25°C)	.....	.....	1.4828
Aniline Point	.....	.....	169°F(76°C)

undesirable suspended materials. Contaminants are introduced into mineral oils from:

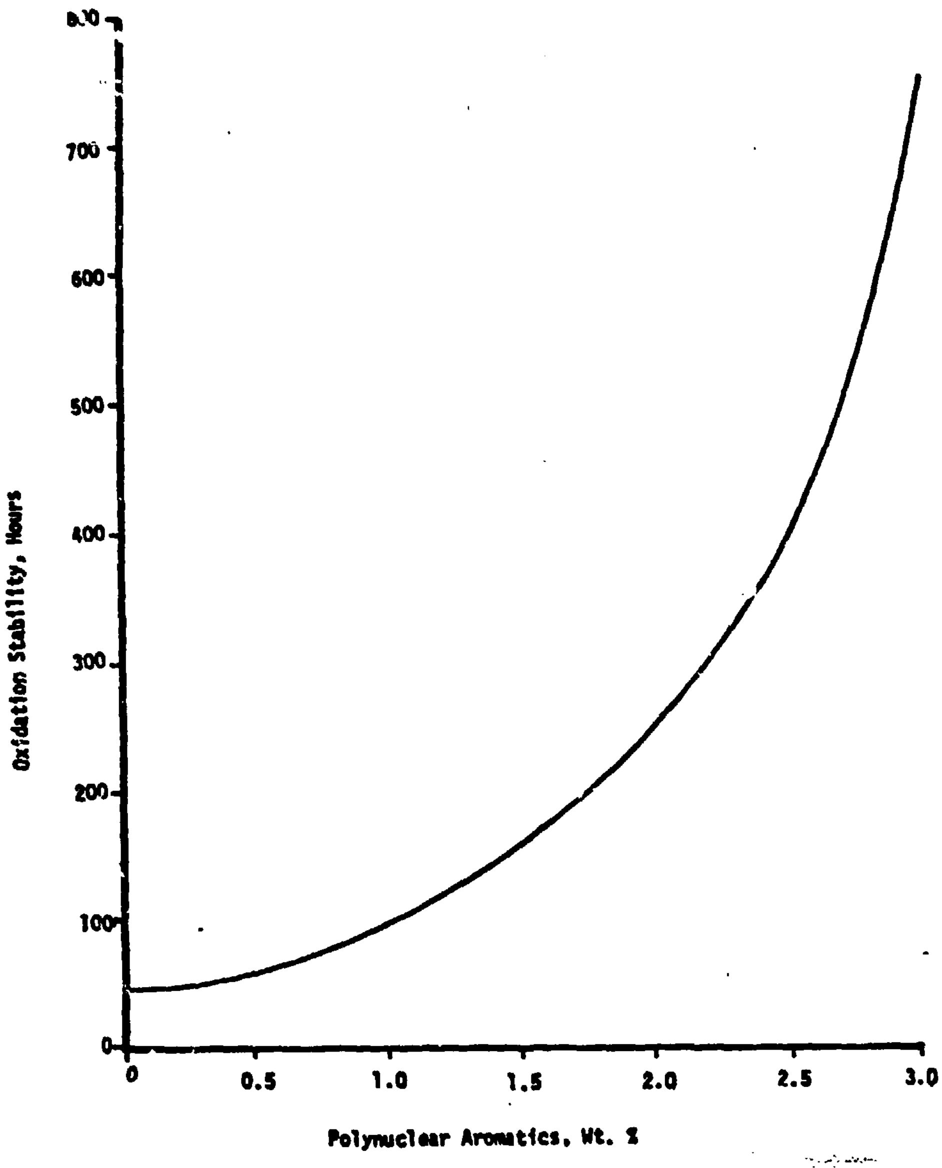


FIGURE 40. OXIDATION OF TRANSFORMER OILS IN ASTM D943 TEST. HOURS TO INTERFACIAL TENSION OF 15 DYN/CM VERSUS POLYNUCLEAR AROMATIC CONTENT OF THE OIL

a) Improper manufacturing and refining methods.
b) Improper handling and shipping procedures.
c) Oxidation of the oil.
d) Soluable polar particles produced by moisture.
e) Improper materials of construction or other insulations.

Construction materials which may or may not be used in contact with mineral oils for long periods of time are shown in Table 12. The interfacial test is a sensitive detector of small concentrations of polar contaminates and oxides. This and other tests necessary in specifying electrical insulating oils are discussed by Clark[64] and by Simo.[68] New methods of accelerated testing and rapid measurement are presented by Harada et. al. [69]

Three types of loss mechanisms are known to exist in mineral oils, all due to contaminates; (1) dipole orientation, (2) space-charge orientation, and (3) ionic conduction.[70] The magnitude of each of these losses in an oil depends on oil temperature, power frequency, oil viscosity, and the degree of contamination of the oil. These losses, particularly with respect to oil impregnated paper, are discussed by Rogers [71] and Sakamoto et. al.[72]

68) Simo, "Large Scale Dielectric Test of Transformer Oil with Uniform Field Electrodes", IEEE Transactions on Electrical Insulation, Vol. EI-5, No. 4, December, 1970, pp. 121-126.

69) T. Harada, et. al, "Short Time AC V-t Characteristics of Oil Gaps", "IEEE Transactions on Electrical Insulation, Vol. EI-16, No. 5, October, 1981, pp. 423-430.

70) R. Bartnikas, "Dielectric Loss in Insulating Liquids, "IEEE Transactions on Electrical Insulation, "Vol. EI-2, No. 1, April 1967, pp. 33-54.

71) R. R. Rogers, "IEEE and IEC Codes to Interpret Incipient Faults in Transformers, Using Gas in Oil Analysis, IEEE, on Insulation, Vol. EI-13, No. 5, October, 1978, pp. 349-354.

72) S. Sakamoto and H. Yamada, "Optical Study of Conduction and Breakdown in Dielectrics Liquids", IEEE, Trans. On Elec. Insulation, Vol. EI-15, No. 3, June 1980, pp 171-181.

New methods of refinement, new additives, new inhibitors, treatments, and new oil blends are being discovered and developed to improve critical parameters of oils without degrading the other parameters in neither oil or oil-solid-dielectric systems.[61, 62, 73, 74, 75]

TABLE 12

MATERIALS COMPATIBILITY WITH MINERAL OILS

Compatible Materials	Incompatible Materials
Alkyd resins	Acrylic plastics
Cellulose esters	Asphalt
Cork	Chloride flux
Epoxy resins	Copper (bare)
Masonite	Fiber board
Melamine resins	Greases
Nylon	Polyvinyl chloride resins
Phenol-formaldehyde resins	Rubber (natural & synthetic)
Polyamide-imides	Saran resins
Polyester-imides	Silicone resins
Polyethylene Terephthalate (Mylar)	Tars
Polyurethane	Waxes (petroleum)
Pressboard	
Shellac	
Silicone rubber	
Wood	

73) B. P. Kang, "Thermal Dependency of Viscosity, Power Factor, and Ion Content on Electrical Insulating Oils-III Predictions of Power Factor of Oil Blends through the Concept of Ion Content," IEEE Transactions on Electrical Insulation, Vol. EI-2, No. 2, August 1967, pp. 121-128.

74) Y. N. Rao and T. S. Ramu, "Determination of the Permittivity and Loss Factor of Mixtures of Liquid Dielectrics," IEEE Transactions on Electrical Insulation, Vol. EI-7, No. 4, December 1972, pp. 195-199.

5.5.7 Askarels. Askarels are synthetic liquid dielectrics used primarily in capacitors and transformers. They are chemically stable, non-flammable, and oxidation resistant. Commercial askarels are derived from aromatic hydrocarbons by chlorination to the extent that a chemical equivalent of chlorine and hydrogen is present in each molecule. When an askarel is decomposed by an electric arc, only non-flammable gaseous mixtures of hydrogen chloride and carbon evolve. Typical characteristics of askarels are shown in Table 13.[64]

Askarels provide dielectric constants that are more than twice those of mineral oils. When used for impregnating paper capacitors, their high dielectric constants permit large decreases in capacitor size. Furthermore, askarels are better than mineral oil with respect to matching the dielectric constant of capacitor paper. This contributes to a more evenly distributed dielectric stress in the capacitor.

The askarel liquids do not oxidize as oils do, but they attack and dissolve a wider range of materials than mineral oils do. A partial list of construction materials which may or may not be used with askarels is shown in Table 14.

The dielectric strength of synthetic liquids is little affected by contaminants, extended high temperatures, or moisture content below saturation. The dielectric loss, though, is increased by contaminants and moisture content.

5.5.8 Silicone Oils. Silicone oils most commonly used as liquid dielectrics are dimethyl silicone polymers. These silicones are characterized by a nearly flat viscosity--temperature relationship, resistance to oxidation, stability at high temperature, and excellent high frequency characteristics. They are unique in two important properties: (1) viscosity range from 1 to

75) R. R. Buntin, R. D. Wesselhoff, and E. O. Forster, "A Study of the Electrical Insulation Characteristics of Oil-Impregnated Polypropylene Paper," IEEE Transactions on Electrical Insulation, Vol. EI-7, No. 4, December 1972, pp. 162-169.

TABLE 13

TYPICAL CHARACTERISTICS AND USES OF ASKAREL INSULATING LIQUIDS

Use	Capacitors	Capacitors	Transformers	Transformers
Condition (25^oC)	Clear	Clear	Clear	Clear
Color	Yellow Tint	Light Yellow	Yellow Tint	Yellow Tint
Acid Value (mgKOH/gr)	$<$ .01	$<$ .01	$<$ .01	$<$ .01
Free Chloride ion	Nil	Nil	Nil	Nil
Specific Gravity (25^oC)	1.40-1.45	1.54-1.55	1.54-1.55	1.55-1.57
Fire Point (^oC)	None	None	None	None
Pour Point (^oC)	0 to -7	6 to 12	-40 to -50	-35 to -40
Viscosity (37.8^oC)	200 (SSU)	3000 (SSU)	42 (SSU)	54 (SSU)
(98.9^oC)	40 (SSU)	46 (SSU)	--	33 (SSU)
(100^oC)	1.2^0(E)	1.4^0(E)	--	--
Coef. of Expansion ($25-65^oC$) (cc/cc/^oC)	68×10^{-5}	65×10^{-5}	67×10^{-5}	67×10^{-5}
Heat Conductivity (40^oC) kcal/m/h/^oC	.091	.087	.087	.087
Refractive Index (20^oC)(D)	1.623	1.638	1.607	1.614
Dielectric Strength($20-90^oC$)				
Kv/cm (VDE)	200	200	200	200
VPM (ASTM)	350	350	350	350
Dielectric Constant	5.3 (20^oC) 4.4 (90^oC)	5.0(20^oC)	4.5(25^oC) 3.9(100^oC)	4.2(25^oC) 3.6(100^oC)
Specific Resistance (90^oC) (ohm-cm)	$1-5 \times 10^{12}$	$1-5 \times 10^{12}$	$1-5 \times 10^{12}$	$1-5 \times 10^{12}$
Power Factor (90^oC)	.015	.015	.01-.05	.01-.05

TABLE 14

MATERIALS COMPATIBILITY WITH ASKARELS

Compatible Materials	Uncompatible Materials
Asbestos	Polymers (natural & synthetic)
Cellulose ester resins (cured)	Rubber (natural & synthetic)
Cellulosic cords	Vegetable oil type paints
Cellulosic pressboard	Vegetable oil type varnishes
Cotton paper	
Epoxy resins (cured)	
Kraft paper	
Linen paper	
Paper	
Phenolic resins (cured)	
Polytetrafluoroethylene	
Polyurethane resins (cured)	
Silicone polymers	
Wood	

1,000,000 centistokes, and (2) stability in air to 150°C, and stability when not exposed to air at 200°C and higher.

Silicone liquids resist oxidation and do not form sludge as do mineral oils. Their stability in the presence of oxygen makes them low in fire and explosion hazard, even at temperatures up to 200°C.

5.5.9 Miscellaneous Insulating Liquids. Other liquid dielectrics include fluorocarbons, vegetable oils, organic esters, and polybutene liquids. They are not commonly used, and are not detailed in this report. Some interesting details on special oils are discussed in this paragraph.

Mammootty and Ramu[76] show that castor oil impregnated capacitors can be used at frequencies from 1 to 6 Khz. However, the tan δ increases with temperatures at these frequencies and the capacitors must be cooled to prevent thermal runaway.

Experiments by Katahoire, et. al[77] show that silicone oil with cross-linked polyethylene spacers is improved by twice that used when testing with nylon spacers. The reduction of electrical stress with and without the spacer interface in silicone oil is shown in figure 41.

It was found by Yasufuku et. al[78] that diarylalkane oil has an excellent radiation-resistance property and is suited as a dielectric fluid for electrical apparatus operating under irradiation conditions. It was also found in their experiments that the sulfur compounds accelerated the corrosive action of the insulating oils. The evolution of gas is an excellent measure of fluids insulation integrity. A comparison of the gas evolution from mineral oils and diarylalkane after $v1.7 \times 10^7$R at room temperature is shown in γ-ray irradiation of Table 15. The viscosity change of the oils is shown after γ-ray irradiation of 1×10^8R at room temperature.

76) K. P. Mammootty and T. S. Ramu, "Analysis of the Dielectric Behavior of Castor Oil Impregnated All-Paper Capacitors", IEEE Transactions in Electrical Insulation, VOl. E.I.-16, No. 5, October 1981, pp 417-422.

77) A. M. S. Katahoire, M. R. Raghureer and E. Kuffel, "Power Frequency and Impulse Voltage Breakdown in Silicone Oil/XLPE Interface", IEEE Transactions on Electrical Insulation, vol. E. I. 16, No. 2, April 1981, P. 97-104.

78) S. Yasufuku, J. Ise, and S. Kobayashi, "Radiation-Induced Degradation Phenomena in Electrical Insulation Oils", IEEE Transactions on Electrical Insulation, Vol EI -13, No. 1, February 1978, pp. 45-50.

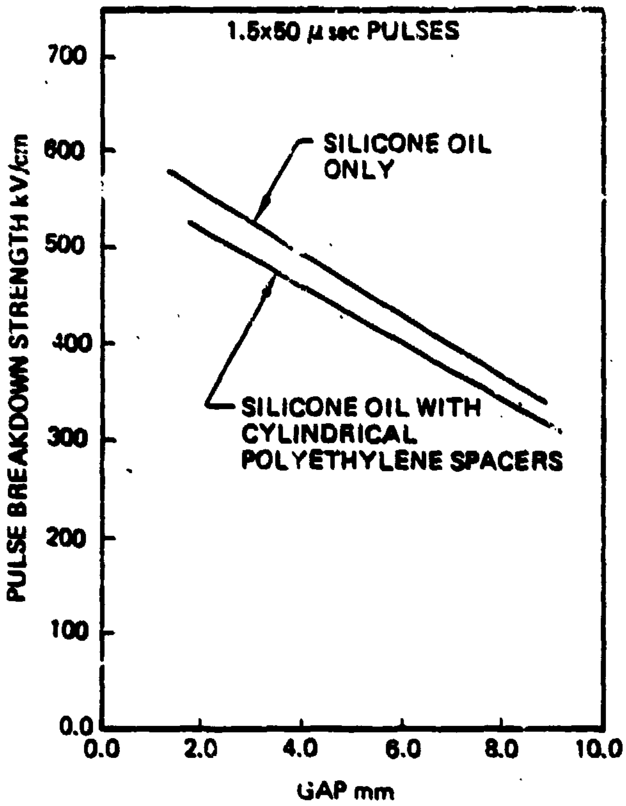


FIGURE 41: SILICONE OIL CROSS LINKED POLYETHYLENE BREAKDOWN UNDER STANDARD POSITIVE PULSE

TABLE 15

GAS EVOLUTION AND VISCOSITY CHANGE AFTER GAMMA IRRADIATION OF 1.7×10^7 R AT ROOM TEMPERATURE

		MINERAL OILS A	MINERAL OILS B	ALKYL NAPHTHALENE	DIARYL ALKANE
GAS EVOLUTION (ml/l)	CO	1.04	0.70	0.08	0.10
	CO_2	3.07	2.92	2.27	2.53
	H_2	296.52	252.76	21.75	8.28
	CH_4	15.51	23.22	2.72	0.94
	C_2H_2	0.06	0.08	0.03	0.03
	C_2H_4	4.85	3.98	0.08	0.00
	C_2H_6	5.54	4.15	0.12	0.00
	C_3H_6	2.07	1.28	0.31	0.00
	C_3H_8	2.88	1.56	1.77	0.00
	$i\text{-}C_4H_{10}$	0.02	0.15	0.01	0.00
	$n\text{-}C_4H_{10}$	0.02	0.03	0.00	0.00
	TOTAL	331.56	290.83	29.14	11.88
VISCOSITY AT 30°C, cS	0	14.00	11.96	21.70	6.69
	5×10^6 R.	14.19	12.01	20.69	6.87
	1×10^7 R.	14.19	12.03	20.17	6.87
	5×10^7 R.	14.71	12.52	20.96	7.04
	1×10^8 R.	15.15	12.90	21.76	7.13

5.5.10 <u>Filtering and Outgassing</u>. Oils used as liquid dielectrics should be filtered before use and outgassed when installed. Mineral oils, vegetable oils, and organic esters should be outgassed at 85°C and at a pressure of 10 N/M^2 (0.7 torr), for four hours.

Oils depressurized to 10^3 to 10^5 N/m^2 (7 to 760 torr) have little change in conduction current at high voltage (to 680 KV/cm) at temperatures below 50°C. At 50°C and higher temperature the conduction current increases as the pressure is decreased below ambient pressure. This is caused by the release of dissolved gas, namely air and oxygen. Further experimental work in this field [79] has showed that the presence of air in oil reduces the affinity of dissolved gases to the oil and bubble formation is increased. This is a strong case for the thorough depressurization of oil.

Where possible, mineral oils and askarels while serving as high-voltage dielectrics, should be continuously circulated through activated alumina, for example by thermosyphon action. Such filtering by controlling contamination, limits the loss at dielectric strength in mineral oil and limits dielectric loss in askarel. [64]

Contaminated oils which do not have the required properties are treated by centrifuging, paper filtration or fuller's earth treatment. Treatment with fuller's earth removes oil soluble moisture, acids and other contaminants.

5.6 <u>Cryogenic Temperatures</u>. Cryogenics refers to the phenomena observed in liquified gases, solid materials and vacuum at temperatures below 100°K. This arbitrary temperature is the threshold below which the properties of dielectrics, liquids, and conductors change significantly.

5.6.1 <u>Cryogenic Liquids</u>. Cryogenic liquids which are likely to be encountered in high-voltage work are listed in Table 16. Their important

79) K. Yoshino, "Dependence of Dielectric Breakdown of Liquids on Molecular Structure", IEEE Transactions on Electrical Insulation, Vol. EI-15, No. 3 June 1980, pp. 186-200.

TABLE 16

BOILING POINTS OF GASES

Substance		Approximate Boiling Point at 1 Atmosphere		
		°C	°F	°K
Helium	He^3	-269.9	-453.8	3.2
Helium	He^4	-268.9	-452.0	4.2
Hydrogen	H_2	-252.8	-423.0	20.3
Deuterium	D_2	-249.5	-417.1	23.6
Tritium	T_2	-248.1	-414.6	25.0
Neon	Ne	-246.0	-410.8	27.1
Nitrogen	N_2	-195.8	-320.4	77.3
Carbon Monoxide	CO	-191.5	-312.7	81.6
Fluorine	F_2	-188.1	-306.6	85.0
Argon	Ar	-185.9	-302.6	87.2
Oxygen	O_2	-183.0	-297.4	90.1
Methane	CH_4	-161.5	-258.7	111.6

physical properties are given in Table 17.[80]

The cryogenic liquids which will probably be used in electrical insulating applications are helium (He^4), hydrogen, and nitrogen. Both hydrogen and nitrogen have higher breakdown voltages than conventional transformer oil, but liquid helium breaks down at a considerably lower voltage.

5.6.2 Dielectric Properties of Cryogenic Liquids. The dissipation losses of liquified helium, hydrogen, and nitrogen are so small they are hard to measure. Published figures for the loss tangent are relative rather than absolute. Comprehensive treatments of techniques for measuring the dissipation loss of cryogenic liquids are published by B.C. Belanger[81], and K.N. Mathes[82, 83]. Measurements of dissipation factor (tangent δ) made by K.N. Mathes[82, 83, 84] are shown in Figures 42 and 43. Measurements were relative rather than absolute. The frequency dependence of the dissipation factor in Figure 42 may be an artifact of the measurement bridge elements.[82]

Pressure does not have much influence on dissipation factor. The rapid increase with voltage stress is thought to be caused by charge injection at the electrodes, an effect that will be covered in the section on the theory of breakdown.

80) H. Weinstock, Cryogenic Technology, Boston Technical Publishers, Inc., Copyright 1969.

81) B.Belanger, "Dielectric Problems in the Development of Resistive Cryogenic and Super-conducting Cables," Conference on Electrical Insulation and Dielectric Phenomena, 1973 Annual Report, p. 486-493.

82) K. N. Mathes, "Dielectric Properties of Cryogenic Liquids," IEEE Transactions on Electrical Insulation, Vol. EI-2, No. 1, p. 24-32, April 1967.

83) K. N. Mathes, "Cryogenic Dielectrics," Conference on Electrical Insulation and Dielectric Phenomena, 1973 Annual Report, p. 547-580.

84) M. J. Jefferies and K. N. Mathes, "Dielectric Loss and Voltage Breakdown in Liquid Nitrogen and Hydrogen," IEEE Transactions on Electrical Insulation, Vol. EI-5, No. 3, p. 83-91, September 1970.

TABLE 17

PHYSICAL DATA FOR CRYOGENIC FLUIDS

Substance		Density: Gas (NTP)[1] g/1	Density: Liquid (NBP)[2] g/1	Volume Ratio Gas (NTP) / Liquid (NBP)	Heat of Vaporization cal/g
He^4	Helium	0.1785	125	700.3	4.9
H_2	Hydrogen	0.08988	71	789.9	108.0
N_2	Nitrogen	1.251	808	645.9	47.6
Ne	Neon	0.8999	1207	1341.1	20.5
F_2	Fluorine	1.696	1510	890.0	41.2
Ar	Argon	1.784	1400	784.0	39.0
O_2	Oxygen	1.429	1142	799.2	50.9
CH_4	Methane	0.7168	415	578.0	121.9

Notes:
1. NTP is Normal Temperature and Pressure 0^oC, $10^5 N/m^2$
2. NBP is Normal Boiling Point at 760 mm

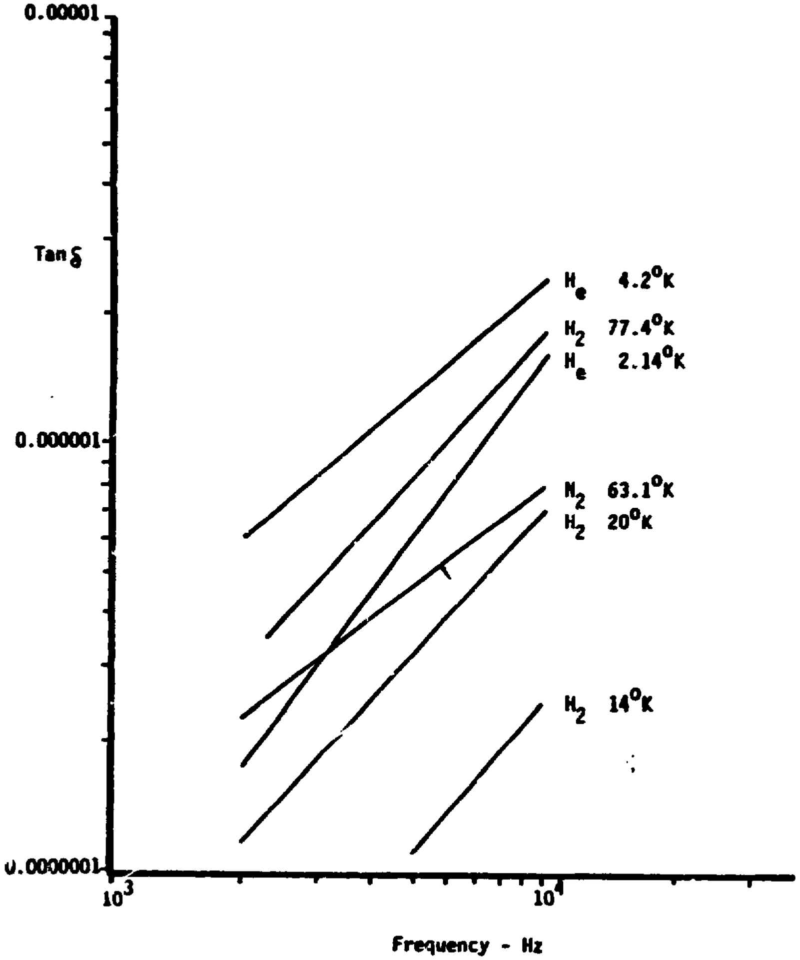


FIGURE 42. DISSIPATION FACTOR AT SEVERAL FREQUENCIES FOR LIQUID HYDROGEN, NITROGEN, AND HELIUM

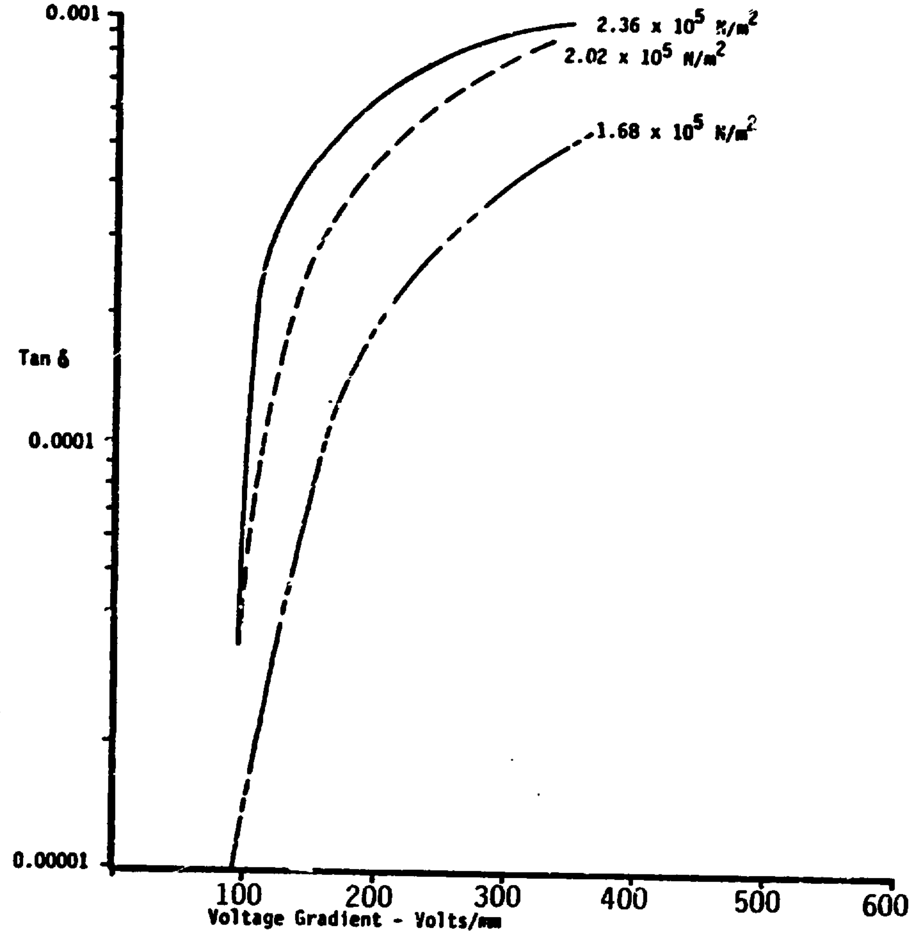


FIGURE 43. DISSIPATION FACTOR VERSUS VOLTAGE GRADIENT FOR LIQUID NITROGEN AT 77°K (NOT BOILING) AND THREE PRESSURES

The dielectric constants of cryogenic liquids appear in Table 18, extracted from the work of R.B. Scott.[85]

Published values of voltage breakdown in liquified helium, hydrogen, and nitrogen must be used with care because the values are sensitive to test conditions. Breakdown voltages measured by various investigations are shown in Table 19.

Details of the test conditions can be found in the cited references. An extensive literature survey and data summarization has been made by Gauster and Schwenterly.[86]

Boiling of the liquified gases at or near the electrodes appears to have no effect on the breakdown voltage. Mathes [82] observed that when the temperature was dropped to freezing (14°K for H, 63°K for N) the breakdown voltage increased considerably (Table 19). Swan and Lewis [94] and T.J. Gallagher[95] showed that the dc dielectric strength of cryogenic liquids was influenced by the metals at the anode and the cathode. (Table 20).

TABLE 18
DIELECTRIC CONSTANT

Liquid	Temperature °K	Dielectric Const.
Helium	4.21	1.0469
	2.21	1.0563
	2.19	1.0563
	2.15	1.0565
	1.83	1.0562
Hydrogen	20.4	1.231
	14.0	1.259
Nitrogen	77.3	1.431
	63.1	1.467

TABLE 19

COMPARISON OF VOLTAGE BREAKDOWN OF CRYOGENIC LIQUIDS

Liquid	Data Source	Electrodes	Spacing (mm)	Temperature °K	Breakdown Strength kV/cm (peak)
He^4	Blaisse, Boogart, & Erne [87]	5mm tungsten sphere to plane	0.05 to 0.15	4.2	720 dc
	Blank, & Edwards [88]	3/8 in. steel spheres	0.15 to 0.5	4.2	1050 to 550 dc
	Goldschvartz, Steeg, Arts, & Blaisse [89]	5mm tungsten sphere to plane	0.01 to 0.1	2.14	1600 to 900 dc
			0.01 to 0.1	4.2	1300 to 850 dc
	Gerhold [90]	25mm sphere to plane	0.1 to 0.5	4.2	700 to 530 dc
	Mathes [82]	1/2 in. steel spheres	0.19	4.2	327 60Hz
			0.5 to 1.0	4.2	319 to 294 60Hz
	Fallou, Galand, Bobo, & Dubois [91]	15mm sphere to plane	0.1 to 7.5	4.2	700 to 150 50Hz
	Fallou, & Bobo [82]	-	5mm	4.2	566 0.02μs impulse
H	Mathes [82]	1/2 in. steel spheres	0.19	20	745 60Hz
		1/2 in. steel spheres	0.19	14	1340 60Hz
N_2	Swan & Lewis [92]	5mm gold spheres	.02 to .1	77.3	1500 dc
		5mm Pt spheres	.02 to .1	77.3	2240 dc
	Blaisse, Boogart, & Erne [87]	5mm tungsten sphere to plane	.05 to .15	65	1600 dc
	Mathes [82]	1/2 in. steel spheres	.19	77.3	805 60Hz
		1/2 in. steel spheres	.19	63	1010 60Hz
	Fallou & Bobo [93]	-	5mm	77.3	240 50Hz
			5mm	77.3	660 .02μs impulse

TABLE 20

INFLUENCE OF ELECTRODE MATERIALS ON THE ELECTRIC STRENGTH OF CRYOGENIC LIQUIDS
(Relative Ratios For Comparison)

Electrode	Argon	Oxygen	Nitrogen
Stainless Steel	1.40	2.38	1.88
Brass	1.01	1.44	1.62
Platinum	1.10	2.00	2.24

85) R. B. Scott, Cryogenic Engineering, New York: Van Nostrand, 1959.

86) W. F. Gauster and J. W. Schwenterly, "Dielectric Strength of Liquids and Gases at Cryogenic Temperatures - A Literature Survey," Appendix A in Cryogenic Dielectrics and Superconducting and Cryogenic Materials Technology for Power Transmission, Oak Ridge Nat.Lab. Rep., TM-4187, May 1973.

87) B. S. Blaisse, A. Van der Boagart and F. Erne, "The Electrical Breakdown in Liquid Helium and Liquid Nitrogen," Bull. Inst. die Froid, p. 330-340 (Annex 1958-1).

88) C. Blank and M. H. Edwards, "Dielectric Breakdown in Liquid Helium," Phys. Rev., Vol. 119, p. 50-52, July 1, 1960.

89) J. M. Goldschvartz, C. Van Steeg, A.F.M. Arts, and B. S. Blaisse, "Conf. Dielectric Liquids," p. 228, Dublin (1972).

90) J. Gerhold, "Cryogenics" 370, October 1972.

91) B. Fallou, J. Galand, J. Bobo, and A. Dubois, Bull. Int. Inst. du Froid, Annexe 1969-1, 377 (1969)

92) D. W. Swan and T. J. Lewis, Proc. Phys. Soc. 78, 448 (1961).

93) B. Fallou, and M. Bobo, "Electrical Properties of Insulating Materials at Cryogenic Temperatures," Conference on Electrical Insulation and Dielectric Phenomena, 1973 Annual Report, p. 514-523.

Polarity also influences DC voltage breakdown as seen in Table 19 for sphere-to-plane and point-to-plane electrode configurations. When the pressure of cryogenic liquids is increased, the voltage breakdown level also increases. Table 21 compares voltage breakdown for a three-fold change in pressure. Additional data has been developed by B. Fallou and M. Bobo [93], and M.J. Jefferies and K.N. Mathes.[84]

TABLE 21

BREAKDOWN VOLTAGE, kV/mm VS PRESSURE (62.5mm SPHERICAL ELECTRODES SPACED 1mm)

	1 Bar	3 Bars	Ratio - 3/1 Bars
Liquid He	18	24.5	1.36
Liquid H_2	28	37.5	1.34
Liquid N_2	29	44.5	1.53

5.6.3 Theory of Conductivity and Breakdown. The conductivity in cryogenic liquids between plane and spherical electrodes is so low that studying the motion of electrons and ions has not been feasible. Recently though, the conduction current has been artifically increased by using sharp pointed electrodes with radii in the order of 1000 Å [96,97]. With this

94) D. W. Swan and T. J. Lewis, "Influence of Electrode Surface Conditions on the Electrical Strength of Liquified Gases," J. Electrochem Soc. 107, 180-185, March 1960.

95) T. J. Gallagher, "Mobility Conduction, and Breakdown in Cryogenic Liquids: A review," Conference on Electrical Insulation and Dielectric Phenomena, 1973 Annual Report, p. 503-513.

96) B. Halbern and R. Gomer, "Journal Chem. Phys." Vol. 43, p. 1069, 1965

97) Y. Takahashi, "Electrical Corona in Liquid Nitrogen," Conference on Electrical Insulation and Dielectric Phenomena, 1974 Annual Report, p. 577-584.

98) A. T. Bulinski, R. J. Densley, and T. S. Sudarshan, "The Aging of Electrical Insulation at Cryogenic Temperatures", IEEE Trans. on Elec. Insulation, Vol. EI-16, No. 2, April 1981, P, 83-88.

"charge-injection" technique, the mobilities of electrons and ions can be studied. He II (superfluid) has a unique characteristic -- the mobility of the positive ion is always greater than that of the negative ion. A summary of the work in this area has been presented by T. J. Gallagher.[95]

Gas bubbles always accompany partial discharges. Takahashi[97], and others believe that the partial discharges are within the gas bubbles.[98] Using the bubble phenomena, D. Peier explains breakdown in liquid N_2 in terms of an avalanche of emulating bubbles.[99] The heat required for formating these gas bubbles might be supplied by electron-molecule collisions which do not lead to ionization. The increase in voltage breakdown with increasing pressure, shown in Table 21, supports this concept of partial discharges in bubbles. Three other theories are summarized and referenced by T.J. Gallagher.[95]

5.6.4 Solid Insulators at Cryogenic Temperatures. Solid insulators at cryogenic temperatures show increased breakdown voltage. They do not experience short term degradation with corona, because of the cryogenic liquid environment. In selecting a solid insulation for low temperatures, consideration must be given to physical properties such as coefficient of thermal contraction, since the materials may crack or develop voids when cooled. Physical properties for many practical materials at cryogenic temperatures were compiled by A. Muller.[100]

The low -temperature dissipation factor for several materials is shown in Figure 44.[93] A. Muller [100] and S.J. Rigby and B.M. Weedy [101] provide a comprehensive list of suitable low-temperature plastics and their dissipation factors.

99) D. Peier, "Breakdown of Liquid Nitrogen in Point-Plane Electrodes," Conference on Electrical Insulation and Dielectric Phenomena, 1974 Annual Report, p. 567-576.

100) A. Muller, "Insulating Tape Characteristics at Cryogenic Temperature," Conference on Electrical Insulation and Dielectric Phenomena, 1973 Annual Report, p. 524-533.

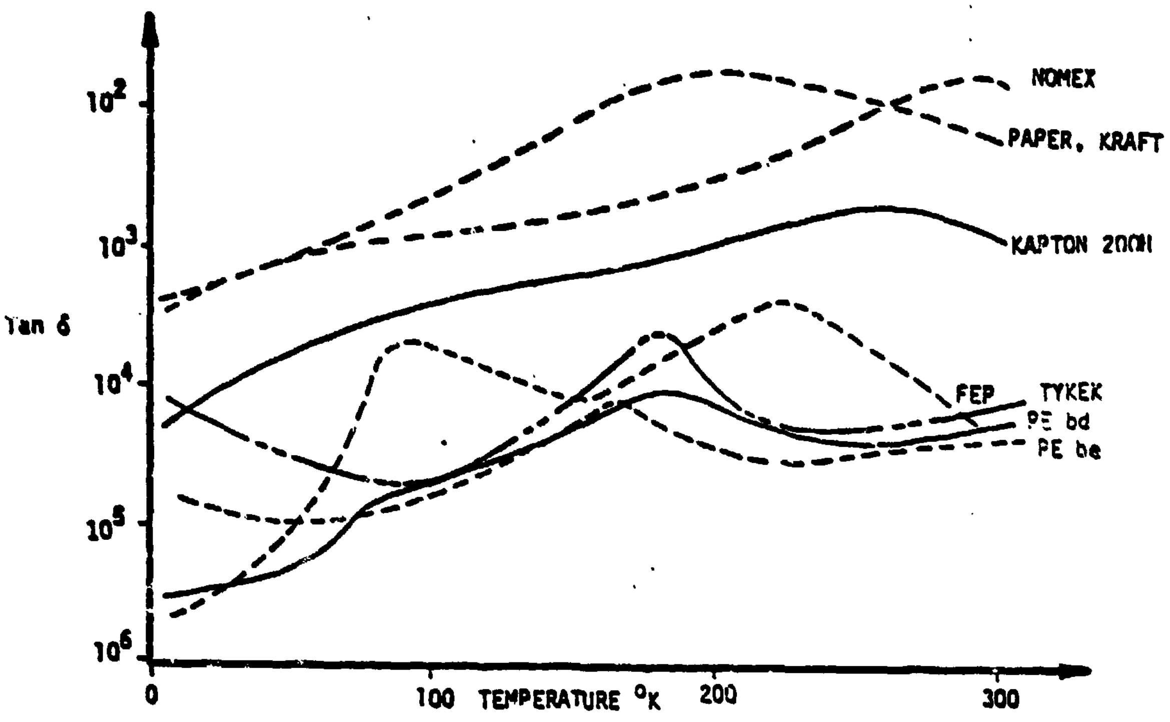


FIGURE 44. DISSIPATION FACTOR AT 1kHz AND UNDER 100 VOLTS

Data on the dielectric strength of solid insulators at cryogenic temperatures is incomplete and the measurements by different investigators often vary considerably. Many measurements have been made with fi because tape wrapped films can be used to insulate high voltage power cables. Some of the published values appear in References 78, and 102 through 105 and Tables 22 and 23.

101) S. J. Rigby and B. M. Weedy, "Liquid Nitrogen Impregnated Tape Insulation for Cryoresistive Cable," IEEE Transactions on Electrical Insulations, Vol. EI-10, No. 1, p. 1-9, March 1975.

102) Z. Iwata, and K. Kikuchi, "Electrical Insulation for Liquid Nitrogen Cooled EHV Cryogenic Cable," Conference on Electrical Insulation and Dielectric Phenomena," 1973 Annual Report, p. 494-502.

103) K. Haga, T. Kajima and Y. Fujuviara, "Development of a Liquid-Nitrogen Cooled Power Cable," Underground Transmission and Distribution Conference, 1974.

Table 22. Breakdown Voltage of
Polymeric Insulation in Liquid Nitrogen

Material - Specimen Configuration	Dimensions mm	Pressure MPa	Breakdown stress ± 95% Confidence Interval kV/mm
Tyvek E.A.C.*	5x0.150	0.2	43.9±2.7
		0.4	50.4±3.9
Tyvek E.C.*	5x0.150	0.2	53.6±5.3
		0.4	64.8±5.9
Tyvek N.C.*	5x0.150	0.2	58.4±2.5
		0.4	73.0±4.8
Nomex E.A.C.*	5x0.125	0.2	53.1±9.3
		0.4	58.6±2.5
Nomex E.C.*	5x0.125	0.4	63.8±1.8
Nomex E.A.C.*	4x0.125	0.2	58.6±2.2
		0.3	55.8±3.3
		0.4	57.7±4.2
Nomex E.C.*	4x0.125	0.2	61.2±5.8
		0.3	60.6±3.6
		0.4	57.2±4.5
Nomex E.C.*	3x0.125	0.1	49.5±3.6
		0.2	56.8±4.9
		0.3	56.9±4.4
		0.4	60.1±2.7
Nomex N.C.*	3x0.125	0.2	65.9±3.0
Nomex E.A.C.*	0.125	0.2	68.2±1.9
	0.05	0.4	70.4±1.9
	0.125		
Nomex E.C.*	0.125	0.1	55.1±3.7
	0.05	0.2	70.8±3.0
	0.125	0.3	73.0±3.0
		0.4	75.6±2.2
Nomex N.C.*	0.125	0.1	64.8±4.5
	0.05	0.2	80.1±2.6
	0.125	0.3	81.2±1.5
		0.4	81.9±7.1

* E.A.C. - electrode adjacent cavity
E.C. - enclosed cavity
N.C. - no cavity

Table 23. Partial Discharge Inception and Extinction Voltages in Polymeric Insulation in Liquid Nitrogen

Material Speciman Configuration	Dimensions	Pressure	Inception Stress in Dielectric	Inception Stress in Cavity		Extinction Stress in Dielectric	Extinction Stress in Cavity		Breakdown Strength	
				N_2Gas	LN_2		N_2Gas	LN_2	N_2Gas	LN_2
	mm	MPa	kV/mm	kV/mm	kV/mm	kV/mm	kV/mm	kV/mm	kV/mm	kV/mm
Polypropylene	0.250									
V.C.#	0.125	0.1	33.2	68.0	44.0	26.6	58.0	35.0	18	58
	0.250									
Polypropylene	0.250									
V.C.#	0.050	0.1	37.0	79.0	49.0	17.0	37.0	23.0	24	95
	0.250									
Nomex	0.125	0.1	36.1	68.2	52.7	16.9	31.9	24.7	24	95
E.C.#	0.050	0.2	48.8	92.2	71.2	45.8	86.6	66.9		
	0.125	0.3	53.3	100.7	77.8	52.5	99.2	76.7		
		0.4	54.7	103.4	79.9	51.8	97.9	75.6		
Nomex	0.125	0.1	42.3			38.0				
N.C.*	0.050	0.2	48.8			49.5				
	0.125	0.3	55.9			55.9				
		0.4	63.3			62.2				
Nomex	0.125	0.1	34.6	65.4	50.5	25.8	48.8	37.7		
E.A.C.*	0.050	0.2	49.9	94.3	72.9	47.9	90.5	69.9		
	0.125	0.3	46.6	88.1	68.0	50.5	95.4	73.7		
		0.4	50.2	94.9	73.3	54.4	102.8	79.4		
Nomex	3x0.125	0.1	34.9	55.8	46.4				18	58
E.C.*		0.2	41.3	66.1	54.9					
		0.3	45.9	73.4	61.0					
		0.4	53.2	85.1	70.8					
Nomex	3x0.125	0.2	44.4							
N.C.*										

TABLE 23 (CONT.)

Material Specimen Configuration	Dimensions	Pressure	Inception Stress in Dielectric	Inception Stress in Cavity		Extinction Stress in Dielectric	Extinction Stress in Cavity		Breakdown Strength	
				N_2 Gas	LN_2		N_2 Gas	LN_2	N_2 Gas	LN_2
	mm	MPa	kV/mm	kV/mm	kV/mm	kV/mm	kV/mm	kV/mm	kV/mm	kV/mm
Nomex E.A.C.*	5x0.125	0.2	33.0	60.4	47.2					
		0.4	42.0	76.9	60.1					
Nomex E.C.*	5x0.125	0.4	48.3	88.4	69.1					
Tyvek E.A.C.*	5x0.150	0.2	43.9	65.5	50.2					
		0.4	50.4	75.2	57.6					
Tyvek E.C.*	5x0.150	0.2	53.6	79.9	61.3					
		0.4	64.8	96.8	74.2					
Tyvek N.C.*	5x0.150	0.2	58.4							
		0.4	73.0							

* V.C. - Vented cavity (Gas vented laterly as between two films)
E.C. - Enclosed cavity
N.C. - No cavity
E.A.C. - Electrode adjacent cavity

5.6.5 Helium. Liquid helium has been masured between IEC (uniform field) and cylindrical electrodes by Gerdinio, et. al.[105] as shown in Table 72. When the minimal of the group's test data for quasi-uniform field area are plotted (Figure 45), a straight-line fit is formed, which is in agreement with data for most liquified gases.

The effects of electrode configuration, spacing, and polarity are shown for short and long pulses in Figure 46[106]. The negative pulses are in agreement with other experimental data for liquid helium. Pulse data measurements are usually taken between either needle points, razor blade edges, or a very small radius point and a plane.

Partial discharges were measured in liquid helium by Weedy and Shaikh[107]. Measurements were made by varying the voltage 400/V/S to inception and to extinction. Discharges of one-picocoulomb were used to determine the exception voltage. The classical inceptive voltage shown by curve a, Figure 46, is compared to the experimental curve (b). The classified curve is always higher than the experimental curve for higher pressures.

104) K. N. Mathes, "Cryogenic Cable Dielectrics", IEEE Transactions on Electrical Insulation, Vol. EI-4, No. 1, p. 2-7, March 1969.

105) P. Girdinio, G. Liberti, P. Molfino, and G. Molinari, "A Statistical Investigation on the Breakdown Strength of Liquid Helium with IEC and Cylindrical Electrodes", Conf. Record of 1982, IEEE International Symposium in Electrical Insulation, 82CH1780-6-EI, June 1982, pp. 272-275.

106) K. Yoshino, "Dependence of Dielectric Breakdown of Liquids on Molecular Structure", IEEE Transactions on Electrical Insulation, Vol. E.I.-15, No. 3, June 1980, pp. 186-200.

107) B. M. Weedy and S. Shaikh, "Partial Discharges in Cavities in Insulation Impregnated with Supercritical Helium", Transactions on Electrical Insulation, Vol. E.I.-17, No. 1, February 1982, pp. 46-52.

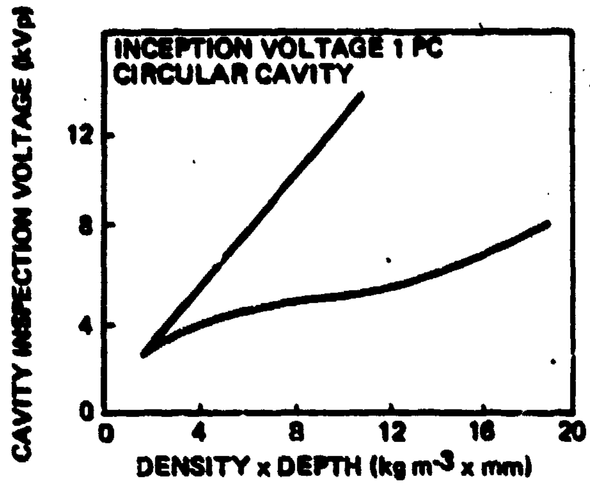


FIGURE 45: INCEPTION VOLTAGE (PEAK) AS A PRODUCT OF HELIUM DENSITY AND CAVITY DEPTH. (a) PASCHEN CURVE FOR HELIUM GAS, 1 mm GAP. (b) BARE METAL ELECTRODES WITH 125 μm GAP; HELIUM AT 0.4 MPa

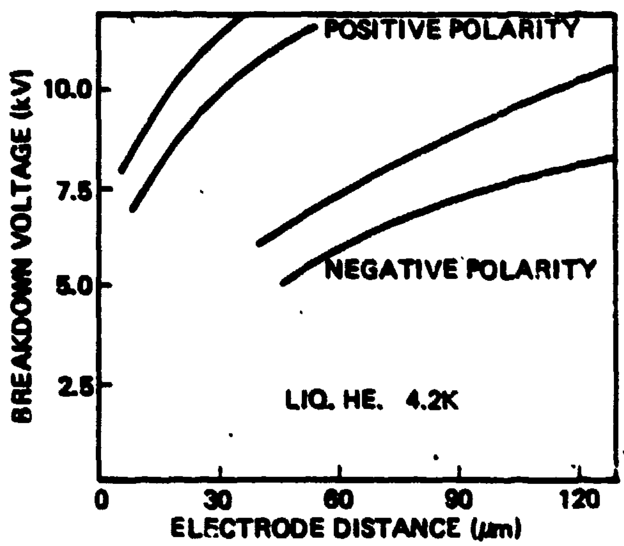


FIGURE 46: POLARITY EFFECT OF BREAKDOWN IN LIQUID He FOR 100 nsec PULSES BETWEEN NEEDLE POINTS

5.6.6 Vacuum at Cryogenic Temperatures. Vacuum insulation at cryogenic temperatures has been investigated.[93,108,109,110] Its main disadvantage is the need to support the conductor with insulators, greatly reducing the breakdown voltage of the combination. Most of the ionic activity preceeding and during breakdown is at the triple junction between metal, dielectric, and vacuum, and along the dielectric surface.[106] P. Graneau and H.M. Schneider have measured breakdown voltage limits and tolerance to multiple electrical discharges. They used glass spacers to support the conductor in the vacuum.[110] To minimize damage from discharges the conductor support insulators must be made from inorganic materials such as glass, alumina, and porcelain.

Vacuum can also be used to enhance the dielectric strength of solid dielectric materials. Data obtained by M. Bobo and published by K.H. Mathes[83] is shown in Table 24.

TABLE 24

50 Hz VOLTAGE BREAKDOWN STRESS, MV/cm rms AT LIQUID HELIUM TEMPERATURE, 4.2°K

	PET Film	FEP Film	Polyimide Film
In Boiling He	1.42	1.55	1.62
In Vacuum, 10^{-7} Torr	2.34	2.18	2.68
In Vacuum Varnished Electrodes	2.9	2.76	3.54

108) J. Juchniewicz and A. Tyman, "Voltage Endurance Test of Vacuum Insulation for Cryo-Cables," IEEE Transactions on Electrical Insulation, Vol. EI-10, No. 4, p. 116-119, December 1975.

109) P. Graneau, "Lichtenberg Figures Produced by High Voltage Discharge in Vacuum," IEEE Transactions on Electrical Insulation, Vol. EI-8, No. 3, p. 87-92, September 1973.

110) P. Graneau and H. M. Schneider, "Vacuum Insulation for Cryo-Cable and its Resistance to Discharges," IEEE Transactions on Electrical Insulation, Vol. EI-9, No. 2, p. 63-68, June 1974.

5.6.7 Application Notes. The dielectric loss is important in high-voltage cryogenic equipment because these losses must be extracted out by refrigeration equipment. For AC cryoresistive cables, a rule of thumb is that the dissipation factor should not exceed 10^{-4}. For superconductive AC cables it should be less than 10^{-5} (see Reference 81).

For long-term reliability, the insulation must be designed to operate below the corona inception voltage when system voltage is normal. Most materials do not degrade during short periods of partial discharge at cryogenic temperatures, because of the inert-liquid environment. We cannot have any bubbles if we are going to avoid partial discharges during normal operation, so the cryogenic liquid must be kept below its boiling point.

5.7 Voltage Stress for Several Electrode Configurations. Electrode configurations can be classified into three general categories: (1) points, which includes sharp corners, sharp bends in wire filaments, and projections from a surface, such as a solder draw; (2) curved surfaces such as long, spaced wires, a round wire close to a ground plane, corona balls, and a coaxial cable; and (3) parallel plates. Each of these electrode configurations has a unique electric field, depending upon the shape of the electrodes and the spacing between the electrodes. For configurations, such as plates, long parallel conductors and coaxial cylinders, the theoretical equations are well known and the field lines are easily drawn. Often the field is non-uniform, as in a transformer or generator winding. Then plotting the field requires much hand labor or access to a computer.

5.7.1 Electric Fields. The space between and surrounding two or more electrodes is regarded as the electric field. Every point within this space has a definite potential which is related to its physical position in the field. The negative gradient of voltage at any point is a vector which is defined as the electric field-strength E at that point. This gradient can be conceived as a force tending to displace a positive charge in the direction of the vector toward the negative electrode. Shown in Figure 47 is a field plot for an energized insulated conductor next to a ground plane. The field lines emanate perpendicularly from the negative electrode and terminate perpendicularly on the positive electrode. Only one field line crosses the gas-solid

dielectric interface at right angles -- the shortest one. At all other points along the interface the field lines cross at an angle.

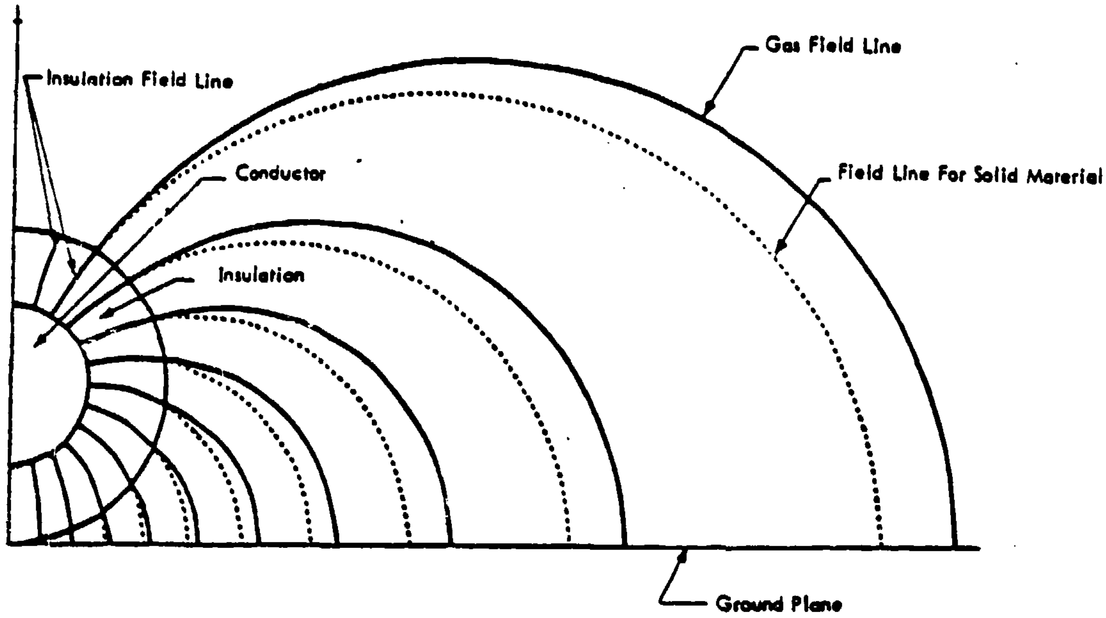


FIGURE 47. FIELD LINES BETWEEN A HIGH VOLTAGE CONDUCTOR AND GROUND

A treatise on electric field theory can be found in most texts on electricity and magnetism, or fields and waves. Von Hipple[7], Greenfield[8], and Schwaiger and Sorensen[111] have written texts on dielectrics which explain the basic principles of field theory. Texts describing field plotting and analysis are by Moore[112, 113] Bewley,[114] Smythe,[4] Stratton[5], and Weber[6].

111) A. Schwaiger and R. W. Sorensen, Theory of Dielectrics, John Wiley and Sons, Inc., New York, New York, 1932.

112) A. D. Moore, Fundamentals of Electric Design, McGraw-Hill Book Company, Inc., New York, New York, 1927.

113) A. D. Moore, "Mapping Techniques Applied to Fluid Mapper Patterns," Trans. AIEE, Vol. 71, 1952.

114) L. V. Bewley, Two-Dimensional Fields in Electric Engineering, The Macmillan Company, New York, New York, 1948.

5.7.2 Configurations. The best shape and spacing of electrodes in electrical/electronic equipment depends upon the physical construction of the equipment, the applied voltage, the type of insulation and gas pressure, and the operating temperature. For a given electrode spacing and at pressure times spacing values greater than 1500 N/m^2-cm, a spark will jump between small-radius electrodes at lower voltage than between electrodes having large radii (Figure 48). This indicates that for a given potential difference and spacing the peak field intensity at the electrodes is smallest when the field is homogeneous (parallel plates) and the field lines are thus parallel. Most parallel plates must have edges where the field is more intense than in the center. By rounding the edges properly, this field can be spread over a greater area, reducing the electric field gradient at the electrode (Rogowski[115]).

For electrodes of any given shape the variation in potential, as a function of the distance from one electrode to the other electrode, can be calculated by solving the differential equations for the electrostatic field. For parallel plates, concentric spheres, and coaxial cylinders the equations for the field strength are:[111]

Parallel Plates

$$E_x = \frac{\partial\phi}{\partial x} = -A = \frac{V}{S} \text{ volts/cm} \quad (3\text{-}26)$$

where: E_x = voltage gradient at distance x between electrodes volts/cm

ϕ = potential at the electrode, volts

x = distance from the reference electrode, cm

A = constant

V = volts

S = spacing between electrodes, cm

115) W. Rogowski and H. Rengier, Arch. Elektrotech., 26, 1926, Page 73.

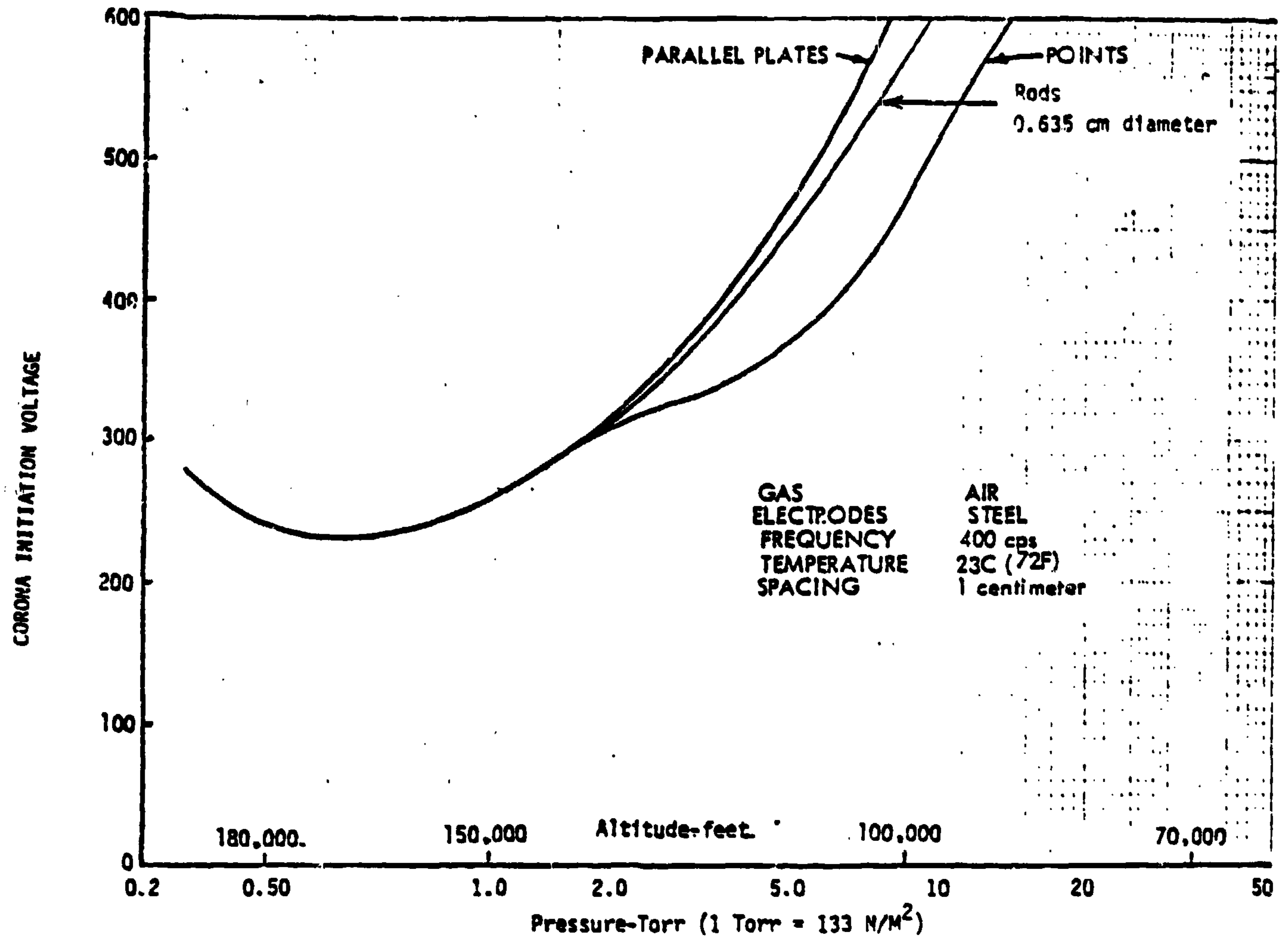


FIGURE 48. CORONA INITIATION VOLTAGE BETWEEN POINTS, RODS, AND PLATES

Concentric Spheres

$$E_x = \frac{V}{x^2} \frac{r_1 r_2}{r_2 - r_1} \tag{3-27}$$

where: $|V_2| > |V_1|$

r_1 = inner sphere (outside) radius, cm

r_2 = outer sphere (inside) radius, cm

V_1 = reference voltage, volts

V_2 = high voltage applied to opposite electrode, volts

The maximum field gradient E_m is at the surface of the smaller sphere where $X = V_1$ is:

$$E_m = \frac{V}{s}\ \frac{r_2}{r_1} \tag{3-28}$$

<u>Coaxial Cylinders</u>

$$E_m = \frac{V}{r_1 \ln(\frac{r_2}{r_1})} \tag{3-29}$$

where: r_1 = inner-conductor outside radius, cm

r_2 = outer-conductor inside radius, cm

E_m = maximum field gradient at the inner conductor surface, V/cm.

Field gradient equations for more complicated electrode configurations are too complex for ordinary design application. Two examples of rigorous solutions for complicated electrodes illustrate the point:

<u>Sphere gap (Reference 111)</u>

The field gradient along the x-axis between two spheres with a charge difference is given below.

$$E_m = \frac{V}{2r}\frac{(1+x)^2}{(1-x)} \sum_{n=0}^{\infty} x^n \left[\frac{1-x^{2n+1}}{(1+x^{2n+1})^2}\right] \tag{3-30}$$

or:

$$E_m = \frac{V}{2r}\ 1+ \frac{(1+x)^3}{1-x}\left[x\ \frac{1-x^3}{(1+x^3)^2} + x^2\left(\frac{1-x^5}{(1+x^5)^2}\right) + x^3\left(\frac{1+x^7}{(1+x^7)^2}\right) + ---\right] \tag{3-31}$$

where: r = radius of the sphere, cm

x = distance from center of the sphere to the point between the spheres, cm

<u>Parallel Cylinders</u> (Reference 114)

$$E_m = \frac{V}{2r}\ \left(\frac{1}{\cosh^{-1}(\frac{s/2 - r}{r})}\right) \tag{3-32}$$

More difficult field patterns can be rigorously calculated using the techniques of References 4, 5, 6, 111, and 114.

5.7.3 Empirical Field Equations. An empirical field equation or formula is the shortened, simplified form of a rigorous equation. Rigorous equations, manageable with electronic calculators, are still difficult ot use in everyday design work; especially if the design has to be assembled piece-wise. Often the equation for the exact required electrode shape is not readily available to the designer. To derive or compute a rigorous equation is an unnecessarily costly and time-consuming process, so it is usually more advantageous to use time-proven empirical equations. Furthermore, the maximum stress is often the only value needed in a design, and the plotting of the complete field using a rigorous equation is not necessary. Empirical equations for the maximum field stresses at the smaller electrodes, for several electrode configurations are given in Table 25.[116] Electrical stresses calculated with these equations are within 10% of values obtained with rigorous equations.

Published empirical equations for sparkover gradients in air and sulfur hexafluoride appear in Tables 2 and 3 .[117] The "typical error" in Table 2 represents the difference between the calculated values and experimental results, except for equations (8) and (9) in Table 3. Here the values represent differences between the rigorous and empirical equations.

The electrode geometries used in Tables 2 and 3 are shown in Figure 49. Parameters for the equations in Tables 2, 3 and 24 are as follows:

E_s = Sparkover gradient, kV/mm

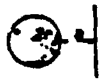
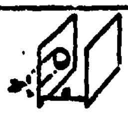
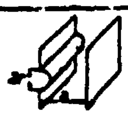
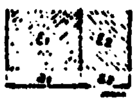
g = Gap length, mm

116) A. Bowers and P. G. Cath, "The Maximum Electrical Field Strength for Several Simple Electrode Configurations," Philips Technical Review, 6, 1941, p. 270.

117) J. M. Mattingley and H. M. Ryan, "Correlation of Breakdown Gradients in Compressed Air and SF_6 for Nonuniform Fields," Conference on Electrical Insulation and Dielectric Phenomena, National Academy of Sciences, Washington, D. C., 1973, pp. 222-233.

TABLE 25

MAXIMUM FIELD STRENGTH E WITH A POTENTIAL DIFFERENCE V BETWEEN THE ELECTRODES, FOR DIFFERENT ELECTRODE CONFIGURATIONS

Configuration		Formula for E
Two parallel plane plates		$\frac{V}{a}$
Two concentric spheres		$\frac{V}{a} \cdot \frac{r+a}{r}$
Sphere and plane plate		$0.9\ \frac{V}{a} \cdot \frac{r+a}{r}$
Two spheres at a distance a from each other.		$0.9\ \frac{V}{a}\ \frac{r+a/2}{r}$
Two coaxial cylinders		$\frac{V}{2.3\ r\ \lg\frac{r+a}{r}}$
Cylinder parallel to plane plate		$0.9\ \frac{V}{2.3\ r\ \lg\frac{r+a}{r}}$
Two parallel cylinders		$0.9\ \frac{V/2}{2.3\ r\ \lg\ \frac{r+a/2}{r}}$
Two perpendicular cylinders		$0.9\ \frac{V/2}{2.3\ r\ \lg\ \frac{r+a/2}{r}}$
Hemisphere on one of two parallel plane plates.		$\frac{3V}{a}$; $(a \gg r)$
Semicylinder on one of two parallel plane plates.		$\frac{2V}{a}$; $(a \gg r)$
Two dielectrics between plane plates (ε_1 ε_2)		$\frac{V\varepsilon_1}{a_1\varepsilon_2 + a_2\varepsilon_1}$

kV = Applied voltage

r_1 = radius of smaller electrode, mm

r_2 = radius of second or larger electrode, mm

s = spacing, center of r_2 to center of r_1, mm

p = pressure, N/m^2

5 7.4 Utilization Factor. The utilization or efficiency factor is defined as the ratio of the field stress between parallel plates and the maximum field stress at the smaller electrode of a non-uniform configuration with identically spaced non-parallel plate electrodes. The utilization factor is numerically equal to the required voltage de-rating. In equation form:

$$n = \frac{E}{E_m} < 1 \qquad (3\text{-}33)$$

where: n = utilization factor

E = voltage stress between parallel plates spaced a unit apart, kV/mm

E_m = maximum voltage stress between two conductors - spaced a unit apart, kV/mm

a = spacing, mm

Plots of the utilization factors as a function of electrode spacing for several electrode geometrics are shown in Figure 49. These geometries are commonly used in many electrical/electronic designs. The utilization factor, which provides a way of quickly estimating the sparkover or breakdown voltage of a configuration. also be used for estimating the minimum electrode radius for a given spacing when the electrical stress capability of the dielectric is known.

5.7.5 Freehand [illegible] d Plotting. For complicated fields, which are very difficult to analyze mathematically, even with computer, freehand flux plotting by the trial and error method is a recourse. Sufficient accuracy may be obtained for most practical engineering problems by plotting the field with "curvilinear" squares. Freehand field plotting techniques are described in Appendix A.

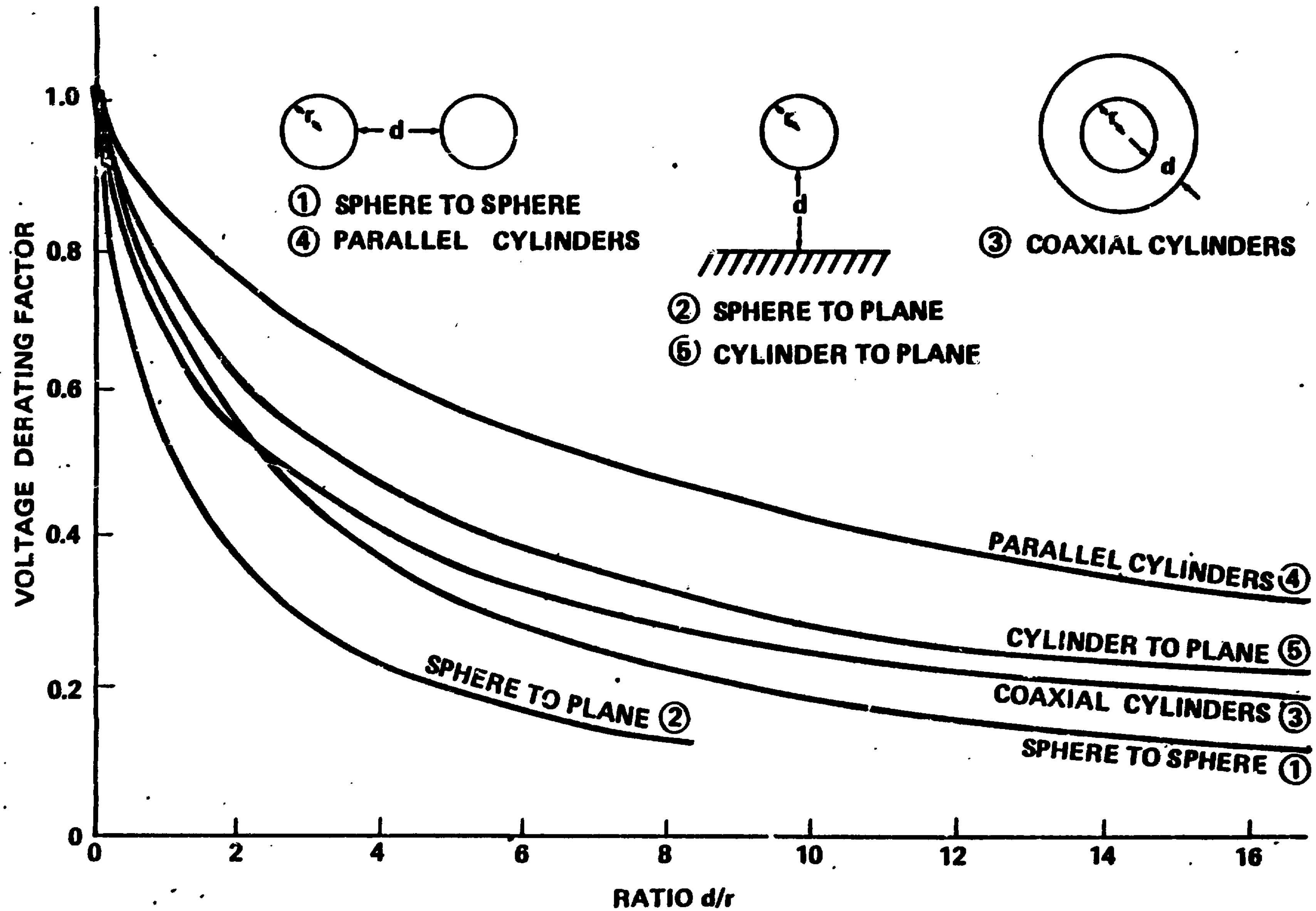


FIGURE 49. UTILIZATION FACTOR FOR VARIOUS ELECTRODE CONFIGURATIONS

5.7.6 Mathematical Mapping Techniques. include:

- o Analytic Solutions
- o Conformal Mapping Techniques
- o Finite-difference Computer Programs
- o Resistance - Network Analogs
- o Conducting - Paper Analogs

For the electronic field problems encountered in the dielectric design of transformers and electric machines, the resistance paper analog gives quick, reliable results and is preferred by many designers. Its versatility makes it easy for the designer to quickly prepare a field plot and directly interpret the results (see Appendix A).

6. EQUIPMENT

The principal function of electrical insulation in equipment is to isolate the conductors from each other and their surroundings, restricting current flow to the isolated conductors. This same insulation must support the conductors and transfer heat away from them. High power, high voltage airborne equipment is densely packaged, so materials with high dielectric strength are required.

6.1 Wiring and Connectors. Partial discharges in the electrical wiring generate noise which is conducted to connected equipment. Typically, the noise signature is between 20 KHz and 20 MHz. If the partial discharges are extensive, noise can also be induced in low-level neighboring circuits. In high frequency systems, as in radar, the wave shapes of the electrical signals can have partial discharges. These partial discharges produce ozone, light, acid, and the deterioration of dielectrics. If corona persists over 100 hours, the dielectric may start to deteriorate and eventually a breakdown will result.

6.1.1 Design Considerations. Voltage, frequency, temperature, ambient gas composition, pressure, radiation, and structural requirements must be known when designing insulation for high-voltage equipment. This includes the steady-state operating voltage and also any higher voltage transients, their duration, and their frequency of repetition.

Air Pressure. The pressure of air between electrodes in the electrostatic field is a parameter in determining location of the minimum zones on the Paschen law curve. This air pressure between electrodes may differ from the surrounding ambient air pressure and it may have transients. With higher temperatures and mechanical stress, air trapped in the insulation layers may rupture or force voids in the insulation when the surrounding air pressure is reduced. Figure 50 and Figure 51 show such voids created by air trapped between the center conductor, and in the outer shield.

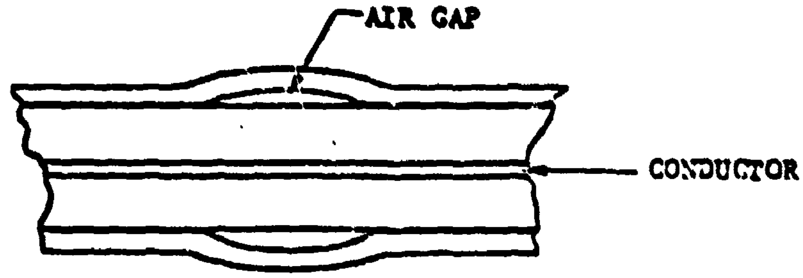


FIGURE 50. OUTER JACKET RUPTURE

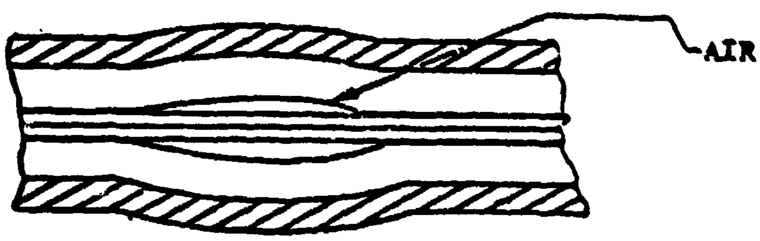


FIGURE 51. CENTER CONDUCTOR DELAMINATION

Temperature. Since each electrical insulation has maximum temperature limits and temperature-life limits, the short-time and continuous temperature, both ambient and local, must be known.

Gases. If the gas between electrodes in the electrostatic field is other than air, Paschen law curves must be determined for that gas.

Environmental conditions. Other environmental factors affecting insulation are ultra-violet and nuclear radiation, and exposure to solvents and chemicals.

Mechanical requirements. Requirements to be satisfied include shock, abrasion, stability, strength, and flexure from vibration.

Frequency. Most of the published aerospace partial discharge initiation voltage data are in terms of 400 Hz, rather than direct current. A formula for comparing dc data with 400 Hz ac data is $V_{ac} = 0.707\ V_{dc}$. The direct current initiation voltage for point-to-plane electrode configurations is affected by the polarity of the point, the configuration with the point negative breaking down at a lower voltage. The ac initiation voltage always corresponds to the dc polarity that has the lower voltage.

At high frequencies, the interference generated by partial discharges is worse than at low frequencies. The rate of deterioration of an insulation by partial dischargesis usually proportional to frequency. The dielectric strength of insulators is inversely proportional to frequency. Typical loss of dielectric strength with frequency is shown in Table 26 for polyethylene and Table 27 for teflon.

TABLE 26

POLYETHYLENE--DIELECTRIC STRENGTH, V/mil, FOR 30-MIL SHEETS AS FUNCTIONS OF TEMPERATURE AND FREQUENCY*

	FREQUENCY						
Temp., °C	60 Hz	1 kHz	38 kHz	180 kHz	2 MHz	18 MHz	100 MHz
-55	1,660	1,270	750	700	410	190	160
25	1,300	970	500	460	340	180	130
50	1,140	910	590	580	280	150	150
80	980	970	440	430	220	150	150

TABLE 27

TEFLON--DIELECTRIC STRENGTH, V/mil, FOR 30-MIL SHEET AS FUNCTION OF TEMPERATURE AND FREQUENCY*.

	FREQUENCY						
Temp., °C	60 Hz	1 kHz	38 kHz	180 kHz	2 MHz	18 MHz	100 MHz
-55	1,080	940	560	600	400	240	160
25	850	810	540	500	380	210	140
50	800	770	530	500	360	210	140
85	780	670	530	430	360	220	140
125	870	630	560	520	350	220	140

6.1.2 High Voltage Cable. At high voltages, special precautions must be taken to eliminate air voids and air gaps from the electrostatic field between conductors. High voltage wire is constructed with conducting layers around the stranded center conductor and just within the outer conductor braid, as shown in Fig. 52. In this construction, the air trapped within the stranded center conductor is not electrically stressed and does not have to be eliminated. The insulation can be advantageously made of several layers, with the dielectric constant (ε) of each layer being successively higher toward the center. The voltage gradient can then be maintained nearly constant from the inner conducting layer to the outer conducting layer, rather than being much higher near the inner conducting layer (Fig. 53). Equations 4-1 through 4-8 are used to compute the dielectric constants or layer thicknesses needed.

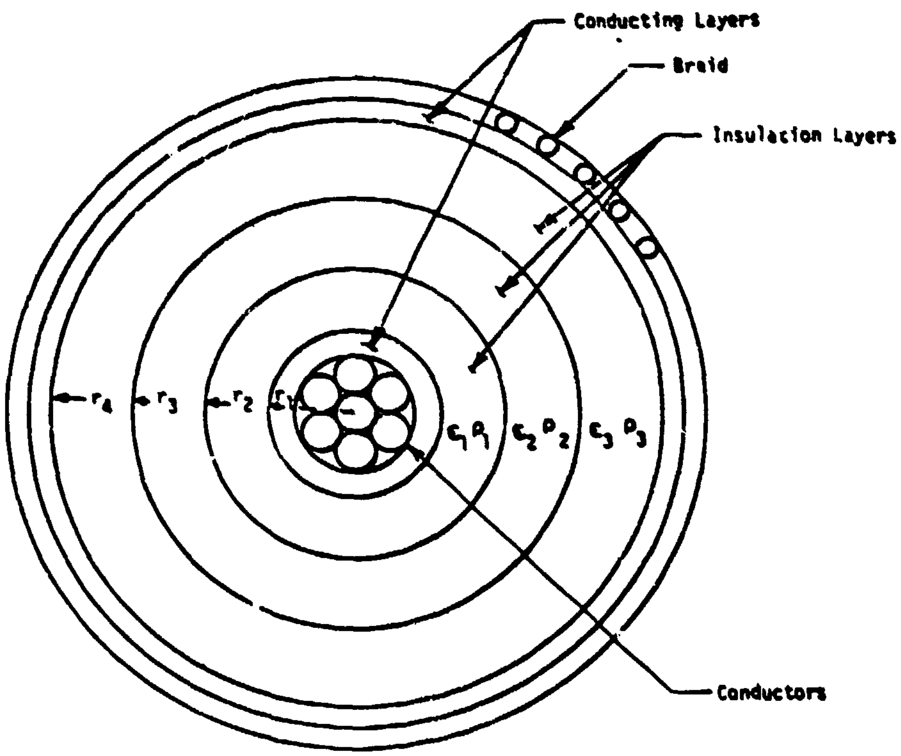


FIGURE 52. · HIGH VOLTAGE WIRE

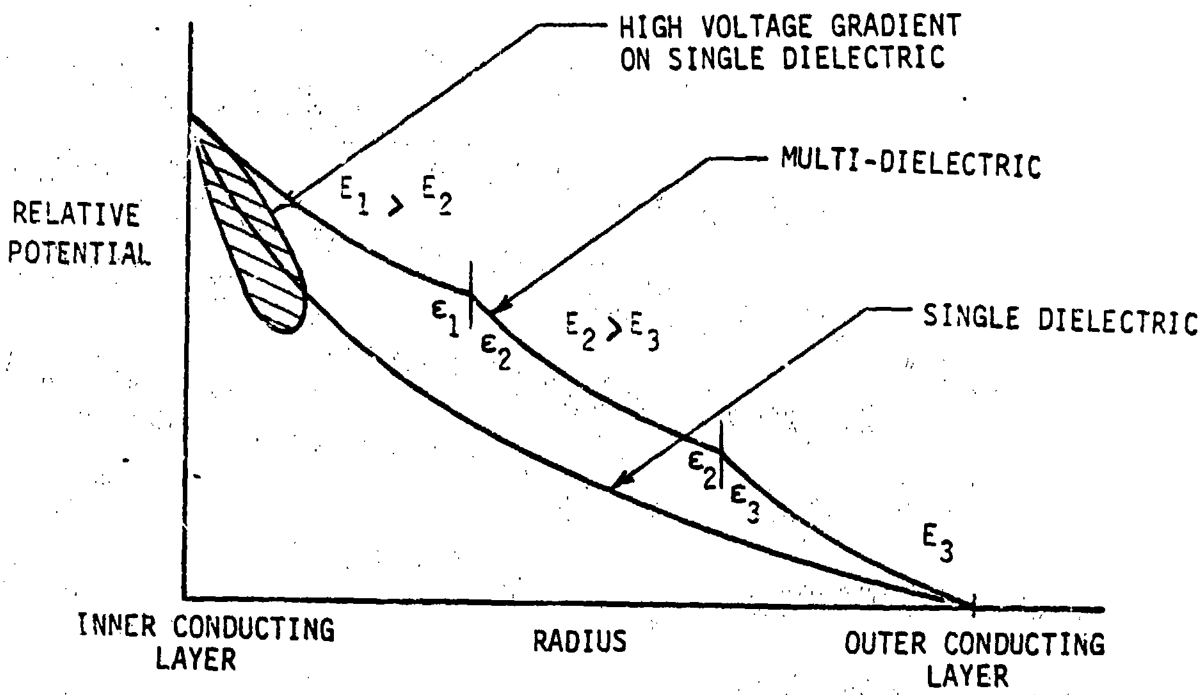


FIGURE 53. FIELD GRADIENT FOR SINGLE AND MULTIPLE LAYER DIELECTRIC

In a coaxial configuration having three layers of insulation (Fig. 52), the voltage stress is not constant across any layer of insulation. In the inner insulation, $\varepsilon_1\rho_1$, the stress (E_1) adjacent to the conductor is in volts per unit of distance

$$E_1 = \frac{V_1}{r_1 \ln (r_2/r_1)} \tag{4-1}$$

The symbols are defined in Fig. 52. The stress within the outer surface of the inner insulation is

$$E_1 = \frac{V_1}{r_2 \ln (r_2/r_1)} \tag{4-2}$$

At the same time, the stress in the $\varepsilon_2\rho_2$ insulation just outside of the interface from insulation ($\varepsilon_1\rho_1$) is

$$E = \frac{\varepsilon_1}{\varepsilon_2}\left(\frac{V_1}{r_2 \ln (r_2/r_1)}\right) \tag{4-3}$$

Continuing in this manner through insulation layer $\varepsilon_3\rho_3$, we can derive an expression for the voltage at the outer surface of the inner layer of insulation.

$$V_o = \frac{V_1 \varepsilon_1}{\ln (r_2/r_1)} \left[\frac{\ln (r_2/r_1)}{\varepsilon_1} + \frac{\ln (r_3/r_2)}{\varepsilon_2} + \frac{\ln (r_4/r_3)}{\varepsilon_3}\right] \quad (4\text{-}4)$$

The other interface voltages can be similarly calculated.

The voltage stress and total allowable voltage when dc is applied to the coaxial configuration in Fig. 52 can be calculated in a similar manner. The stress at the conductor is given by

$$E_1 = \left[\frac{V_1}{\ln (r_2/r_1)}\right]\frac{1}{r_1} \quad (4\text{-}5)$$

The stress at the interface between insulation $(\varepsilon_1\rho_1)$ and $(\varepsilon_2\rho_2)$ changes as one crosses the interface. In insulation $(\varepsilon_1\rho_1)$, the stress is

$$E_1' = \left[\frac{V_1}{\ln (r_2/r_1)}\right]\frac{1}{r_2} \quad (4\text{-}6)$$

while in insulation $(\varepsilon_2\rho_2)$, the stress is

$$E_2' = \left[\frac{V_2}{\ln (r_3/r_2)}\right]\frac{1}{r_2} = \left[\frac{V_1}{\ln (r_2/r_1)}\right]\frac{1}{r_2}\left[\frac{\ln (r_3/r_2)}{\ln (r_2/r_1)}\right]\frac{\rho_2}{\rho_1} \quad (4\text{-}7)$$

and finally

$$V_o = V_1 \left[\frac{\rho_1 \ln (r_2/r_1) + \rho_2 \ln (r_3/r_2) + \rho_3 \ln (r_4/r_3)}{\rho_1 \ln (r_2/r_1)}\right] \quad (4\text{-}8)$$

6.1.3 High Voltage Connectors. Connectors must also be designed to eliminate air voids between conducting surfaces. One successful method is to make one side of the mating-interface from soft pliable insulation (Fig. 54). When mated, the pliable insulation conforms closely to the opposite dielectric. The pliable insulation should first contact the molded insulation near the center conductor, then the contact should progress out to the shell, without trapping air space.

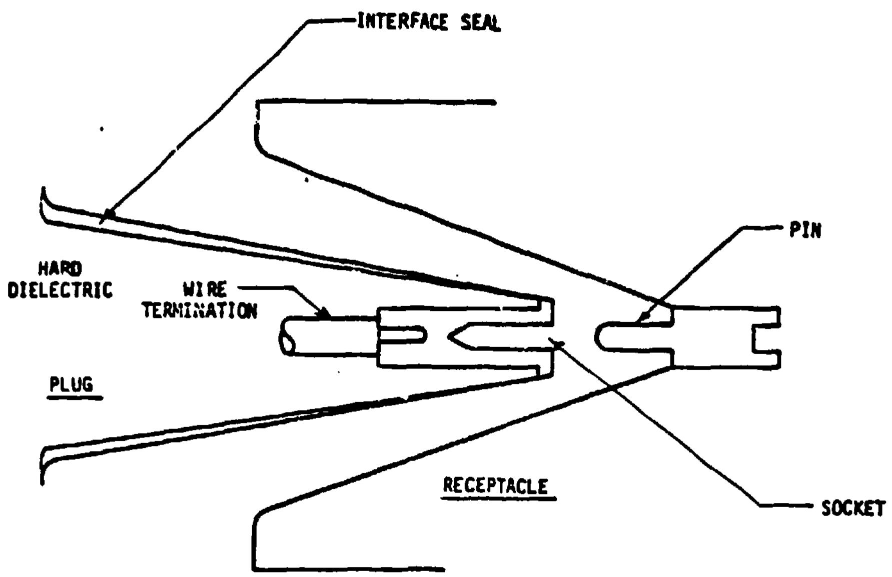


FIGURE 54. HIGH VOLTAGE CONNECTOR

A thin layer of silicon grease has been applied to the insulation surfaces of some connectors to fill micropores in the insulation. Too much grease (more than 5 mils) has a tendency to prevent complete closure of the connector, introduce air cavities, or deform the pliable insulation. Therefore, silicone or other additives are not recommended for properly constructed high-voltage connectors. A properly constructed connector has complete mating on all insulated surfaces of the plug and receptacle.

6.2 Capacitors. High voltage capacitors include voltage ratings of over 2000V or 1000V rms. This threshold is strictly arbitrary and is based on the observation that above these voltage ratings it is usually advisable to connect capacitance elements in series rather than to use a single dielectric pad to withstand the total voltage.

Dielectrics used for high voltage include liquid impregnated paper, plastic film, paper-plastic combinations, mica, ceramics, glass, compressed gas, and vacuum. Unless special requirements with respect to temperature, stability, radiation resistance, or packaging are involved, liquid impregnated paper or plastic offer the best energy-space-cost combination and consequently are more widely available.

This section deals only with high voltage capacitors. Many dielectric configurations which are quite appropriate for low voltage, high performance capacitors for solid-state communication equipment are not applicable to high voltage work, and are not covered here. This excluded category includes electrolytic and ceramic-insulators capacitor types.

Design Features. Design features are strongly influenced by the intended application. The most important design feature of capacitors is the use of the lowest dissipation factor consistent with the dielectric stress that yields an acceptable failure rate. DC capacitors for continuous duty also require low dissipation factor since some AC ripple is usually present. High insulation resistance is also usually required for applications. DC energy storage capacitors require design features that permit extremely high currents as well as very fast charge and discharge rates.

6.2.1 Construction and Processing. Construction and processing have a major effect on high-voltage capacitors performance. Series connection of sections necessitates careful attention to conductor insulation, clearances, geometry, and workmanship while the necessity for liquid impregnation requires meticulous control of materials purity, initially as well as prevention of contamination during processing.

6.2.2 Dielectrics. Liquid impregnation is the most effective means of assuring corona-free performance at rated voltage. All papers and films have surface irregularities that trap air when they are stacked between metal electrodes. Unless the air is replaced by a liquid with dielectric constant reasonably close to that of the paper or film, the stress distribution under an applied potential will be such that the highest stress will appear across the air pockets. Since the air has a dielectric strength far lower than the paper, film or liquid, it will ionize and initiate partial discharges at a potential much lower than that required if no air were present. Under dc-voltage stress, the mechanism is similar except that the stress distribution is controlled by the resistivity of the dielectric materials rather than by their dielectric constants. Another advantage of liquid impregnation is that air, with a dielectric constant of 1.0, is replaced by oils or askarels with dielectric constants of more than five, resulting in a more compact capacitor.

Impregnation with solids such as waxes or resins is feasible for applications but has not been found to be reliable for operation at voltages above 225 volts rms because of susceptability to partial discharge damage. Unimpregnated plastic film capacitors are also suitable for applications but are subject to partial discharge damage at ac voltage above 225 volts rms unless special design features are provided.

6.2.3 Essential Design Features. In addition to the requirements listed below, all types of high-voltage capacitors must be made from dielectric materials having the highest available dielectric strength and having the longest demonstrated life at rated stress.

Capacitor Requirements

AC Capacitors	DC Capacitors	Energy Storage Capacitors
Low dissipation factor	Low dissipation factor	Low equivalent series resistance (ESR)
High partial discharge threshold	Low insulation resistance	Low insulation resistance
		High current capacity
		Low inductance

Dielectrics successfully used in high voltage capacitors include, but are not limited to, the following materials:

Polystyrene dielectric capacitors. Capacitors of polystyrene dielectric, because of their low dielectric absorption and radio frequency losses, are intended primarily for use in calculators, computers, integrators; time-base oscillators, laboratory standards, and other pulse applications. The oustanding characteristics of these capacitors are low temperature coefficient and stability.

Polyethylene terephthalate dielectric capacitors. Capacitors of polyethylene terephthalate dielectric are intended for use in high temperature applications similar to those served by hermetically sealed paper capacitors, but where higher insulation resistance at the upper temperature limits is required.

Paper and polyethylene terephthalate dielectric capacitors. Capacitors of paper and polyethylene terephthalte dielectric are intended for applications where small case sizes and high temperature operation are required.

Polytetrafluoroethylene dielectric capacitors Capacitors of polytetrafluoroethylene dielectric are intended for high temperature applications where high insulation resistance, small capacitance change, and low dielectric absorption are required. These capacitors exhibit excellent insulation resistance values at high temperatures.

Polycarbonate dielectric capacitors. Capacitors of polycarbonate dielectric are especially suitable for use in tuned circuits and precision timing due to their capacitance stability and minimum capacitance change with temperature.

Castor oil and cyanoethyl sucrose. These impregnating liquids tend to freeze at -20°C and are unacceptable for airborne equipment.

Arachlor. The Arachlor glycol and some high dielectric constant materials cannot be used because theyhave low volume resistivities.

Acceptable impregnates. Acceptable impregnates for high voltage capacitors include, but are not limited to, the materials listed below.

Impregnant	Dielectric Constant
Tricresyl Phosphate (TCP)	6.9
Monoisopropyl Biphenyl (MIPB)	2.5
Silicone Oil (DC-200)	3.6
Diallyl phthalate Nomomer (DAP)	10.0

K-F polymer/silicone oil. Polyvinylidene fluoride film (K-F polymer) impregnated with silicone oil perform well in pulse capacitors.[118]

K-F polymer/DAP. K-F polymer impregnated with diallylphthalate has excellent radiation resistance but some interaction was observed between the DAP and K-F polymer.[118]

Polysulfone film. Polysulfone film is an acceptable film for high voltage capacitors.[119]

118) A. Ramus, "Development of a High Density Capacitor for Plasma Thrustor", AFRPL-TR-80-35, Air Force Rocket Propulsion Laboratory, Air Force Systems Command, Edwards AFB, California, May 1980.

119) E. P. Bullwinkel and A. R. Taylor, Final Report, Improved Capacitor Dielectrics for High-Energy Density Capacitors, The Schweitzer Company, Kimberly-Clark Corp., Lee, MA, May 1982.

6.2.4 Failure Modes and Mechanisms. Failure modes in capacitors include short circuits, open circuits, and parameter drift, of which shorts are by far the most frequent. Shorts may result from one of many mechanisms, the most common being electrical breakdown caused by conducting sites or electrically weak areas in the dielectric. Conducting sites may be particles imbedded in the paper, airborne particles picked up during assembly, foil slivers, or products generated by partial discharge. Weak areas may result from torn paper, thin spots, or dielectric layers missed during assembly.

Even a moderate sized capacitor has many square centimeters of dielectric which has to be ultra thin to achieve reasonably small volume. Consequently stresses in capacitor dielectrics are usually far higher than in dielectrics used in other insulation applications. Measures to assure the highest possible electrical strength and longest life of capacitor dielectrics include multi-layer pads, liquid impregnation, use of series connections for voltage ratings above about 2500 volts, assembly in a controlled environment, high potential testing and, in some cases, burn-in at elevated voltage and temperature.

Even the best dielectric papers contain a finite number of conducting particles of randomly distributed sizes, randomly located in position. Multi-layer construction has least chance of having a conducting particle completely bridge the foil electrodes. Since the thinnest paper contains the most conducting particles (full thickness of paper) per square foot, it is desirable to use the thickest paper possible to keep the number of particles low. However, the thinnest possible paper gives the highest capacity per unit volume. A compromise is therefore necessary.

The dielectric strength of a paper pad increases with the number of layers up to four or five layers. Above this number the increase in strength is no longer proportional to the increase in number of layers. There is also an apparent decrease in electrical strength per unit thickness with individual paper thicknesses greater than 0.75 mils. This appears to be an effect of voltage gradient across the dielectric. It therefore becomes advisable to assemble the capacitor by connecting sections in series rather than using thicker pads.

Plastic films such as polyethylene terephthalate (MYLAR) are able to withstand stresses as high as impregnated paper can but the resulting capacitors are generally larger and more expensive for the same performance. Liquid impregnated paper-polypropylene sandwich dielectrics are competitive with liquid impregnated paper but not as widely used because there are fewer reliable sources of supply.

Parameter drift and open circuits are not commonly encountered failure modes in high voltage capacitors, but there have been instances where inexperienced manufacturers have tried to connect to the aluminum foil electrodes by pressure contact rather than by soldering or welding. This is always disastrous because aluminum oxidizes generating open circuits under low voltage stress and destructive arcing under ac.

With liquid-impregnated capacitors the container terminations and seals are important. All free space must be filled with liquid to preclude gas that can ionize. Rectangular or oval cases are designed with enough flexibility to permit the liquid to expand and contract as temperature and pressure change. Cylindrical or rigid walled cases must be designed with provisions that prevent low pressure gas accumulation between plates.

6.2.5 Effects of Partial Discharges. The life of an insulating material depends upon its type, the operating temperature, voltage stress, applied voltage, physical dimensions, materials control during manufacture, and cleanliness. Also important are small defects in the layers of conducting foil and insulation which may become gas-filled voids. Partial discharges can be generated when the gas is overstressed. These discharges are accompanied by electron bombardment which generates hot spots and acts on the air to produce ozone and nitrous oxides that decompose surrounding materials. Damage to the electrical insulation by electron bombardment and chemical deterioration can be identified by a decrease in insulation resistance and an increase in the dissipation factor. Dielectric materials are often evaluated with breakdown tests, superior materials being expected to exhibit higher breakdown voltages. A breakdown test is useful in finding flaws in the insulation. However, where a solid dielectric is to be impregnated with a liquid or when air voids may be present, the value of a breakdown test may be limited because

breakdown values are usually considerably higher than the voltage at which the insulation is used. This point is illustrated in Fig. 55 which shows the relative breakdown values, where partial discharges start and the range of the useful electrical stresses.

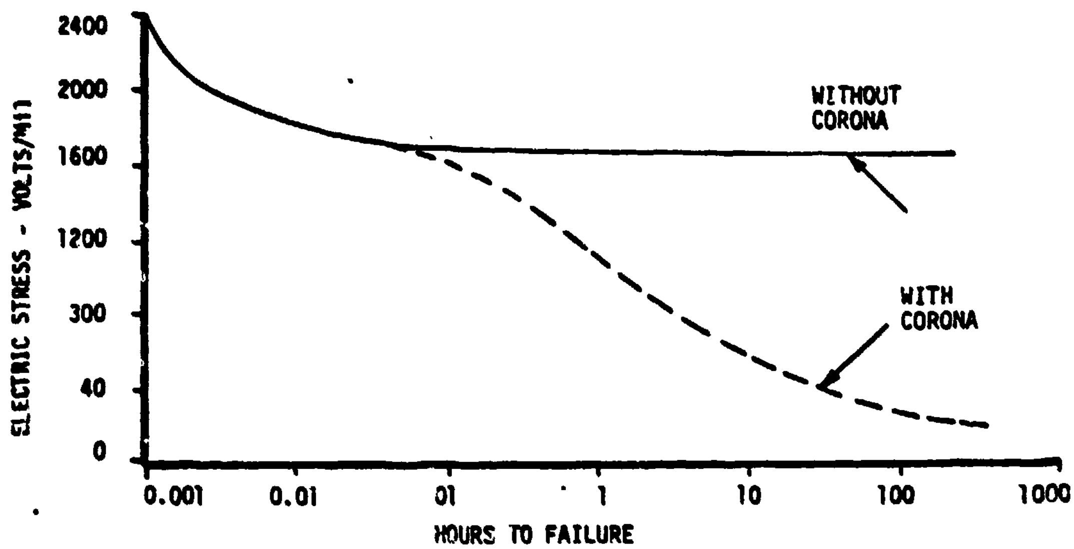


FIGURE 55. DIELECTRIC LIFE OF POLYETHYLENE WITH & WITHOUT CORONA

The discharge inception voltage is very important because a capacitor, if permitted to operate with internal partial discharges, will soon fail as shown in Fig. 55, for polyethelene insulation. Other insulation materials will degrade similarly.

Impregnated paper. As impregnating dielectric liquids age, their molecules polymerize. High temperature and electrical stress accelerate polymerization. In time, continued electron bombardment will carbonize the polymerized molecules and voltage breakdown or puncture of the insulation results.

Gas voids. The partial discharge initiation voltage for gas-filled voids is much lower for solid and impregnated paper dielectrics. Gas-filled voids result from incomplete impregnation during manufacture and must be

detected and eliminated. Dry unimpregnated areas in the insulating paper contain minute voids. Gas-filled voids may also be found at the ends of the individual layers of insulating paper. Also small wrinkles may be formed in the capacitor foil during manufacture. If these small wrinkles are not completely impregnated or filled with solid or liquid insulation, gas-filled voids will be present.

The temperature of the partial discharge across the center of a gas-filled void could be as high as 4,000°K.[120] The gas itself will be much cooler than the discharge channel, around 550°C. The partial discharge inception voltage (PDIV) across a gas-filled void can be as low as 230 volts rms, at the Paschen-law minimum. After gases such as hydrogen or a hydro-carbon gas evolves the PDIV can decrease to 185 to 200 volts, depending upon the breakdown characteristics of the gas or gases and thickness of the series dielectric.

6.2.6 Failure Rate Prediction. Capacitor life is, as expected, dependent on voltage stress and temperature. The relationship can best be described by a failure rate expressed as the percentage of failures (per 1000 unit-hours) based on a specific confidence level. In continuous operation at rated voltage capacitors exhibit a relatively high initial failure rate, called infant mortality, lasting a few hour decades. This is followed by years of essentially constant or slightly decreasing failure rate and finally a rapidly increasing failure rate as wearout become predominant. This is illustrated by the classical "bathtub" shaped curve (Figure 56).

It is feasible to relate life or long time breakdown to commonly used values of dielectric strength. Dielectric strength is measured on small specimens during a "life" on the order of 60 seconds, whereas end-of-life breakdown levels of a large specimen such as a capacitor are subject to an area effect as well as long term chemical and physical changes.

A review of that data shows a trend for partial dishcarges to vary over the life of a dielectric. The measured partial discharges for a new capacitor will have a multitude of low energy partial discharges with a few high energy partial discharges as shown in curve a, Figure 57. As the dielectric ages the number of high energy partial discharges increase indicating there is increase dielectric heating and nearing end of life as shown in curve b, Figure 57.

120) J. M. Meek and J. D. Craggs, Electrical Breakdown of Gases, Oxford at the Clarendon Press, London, England, 1953, pp. 415-421.

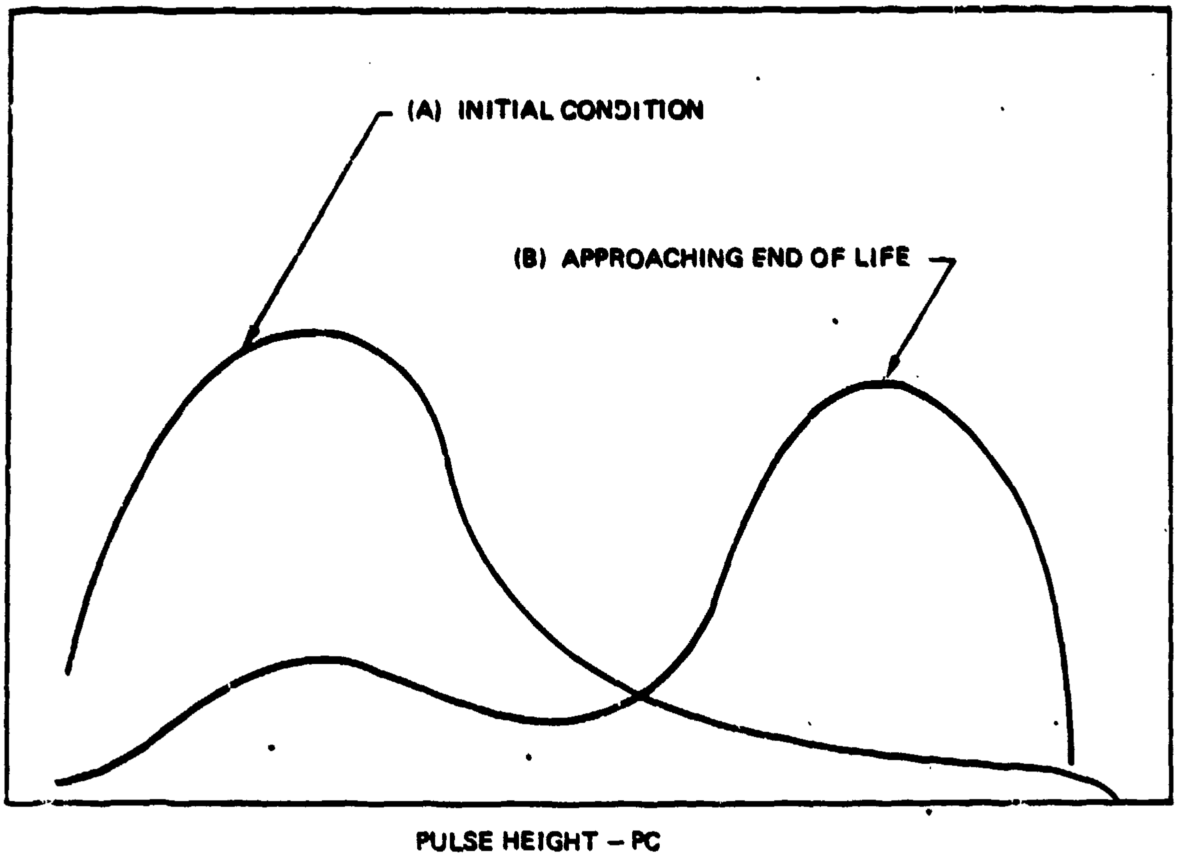


FIGURE 56: CHANGE IN PARTIAL DISCHARGE SIGNATURE WITH TIME OF OPERATION

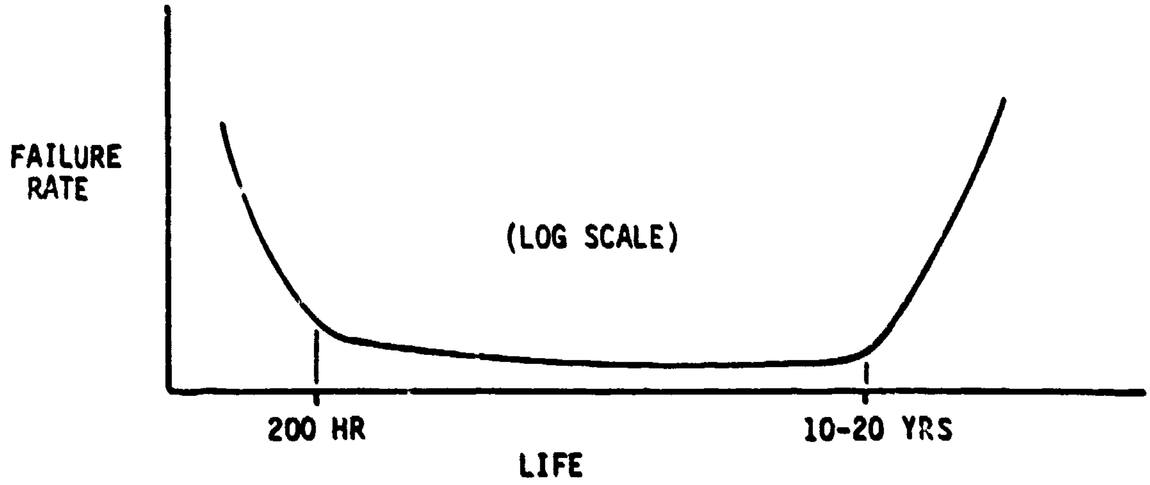


FIGURE 57. FAILURE RATE OF CAPACITORS

Voltage ratings of capacitors are based on life tests using many samples at many voltages and temperatures. Short-time overvoltage tests during manufacturing stages screen out grossly defective parts, but cannot be depended on to reject marginal parts. A burn-in at elevated voltage and temperature is effective in reducing infant mortality of capacitors when reliability is more important than cost. Burn-in is not customarily performed on non-military capacitors. Failure rate data is the basis of reliability-level predictions for established reliability parts, which are then derated to achieve a specific level of reliability. Acceleration factors have been estimated for most types of capacitors, but are not readily available for high voltage capacitors since very few high voltage capacitors are built to military specifications.

The relationship of failure rate to voltage and temperature can be expressed as:

$$\lambda_{\mu} = \lambda_r K^{(T_u - T_r)} \left(\frac{V_u}{V_r}\right)^n \qquad (4\text{-}9)$$

Where: λ_{μ} = failure rate at use conditions

λ_r = failure rate at rated conditions

k = temperature acceleration constant

T_u = use temperature (^{o}C)

T_r = rated temperature (^{o}C)

V_u = use voltage

V_r = rated voltage

n = voltage acceleration factor

The following are values of constants k and n for some common dielectrics:

	k		n	
Dielectric	DC	AC	DC	AC
Mineral oil-paper	1.07	1.036	5	5
Askarel-Paper	-	1.09	5	5.6
MYLAR	1.07	-	5-7	-

Published data relating voltage to dielectric thickness for a given lifetime are always based on some specified active area of dielectric. This voltage must be derated by a factor which depends upon the ratios of the active area of the capacitor being designed and the active area of the test sample (Fig. 57).

6.2.7 Check List of Significant Characteristics. In selecting the most appropriate capacitor for a particular application, the following characteristics should be considered in relation to application requirements in the interest of attaining the optimum balance of producibility, performance and cost.

CAPACITANCE
- Rated value
- Tolerance
- Retrace
- Effect of:
  - Temperature
  - Voltage
  - Age
  - Pressure
  - Frequency

VOLTAGE RATING
- DC continuous
- DC Transient
- Polarity
- AC low frequency
- AC high frequency, RF

TEMPERATURE CAPABILITY

DISSIPATION FACTOR OR Q
- Power factor
- Equivalent series R
  - Effect of:
    - Temperature
    - Voltage
    - Frequency
    - Capacitance

LEAKAGE CURRENT OR INSULATION RESISTANCE
- Effect of:
  - Temperature
  - Polarity
  - Age
  - Voltage

STRAY CAPACITANCE AND RESISTANCE TO CASE

IMPEDANCE
- Effect of:
  - Frequency
  - Series R
  - Series X_L

RIPPLE/PULSE CURRENT

FAILURE RATE
- Effect of:
  - Voltage
  - Temperature
  - Ripple current
  - Transients

FAILURE MODES

NOISE

VOLUME & WEIGHT PER uF VOLT OR PER KVAR

MECHANICAL FEATURES
- Enclosure
- Mounting provisions
- Seal
- Flammability
- Effect of:
  - Orientation
  - Vibration
  - Shock
  - Humidity

COST

AVAILABILITY

6.3 Magnetic Devices. Motors, generators, transformers, and inductors are magnetic devices requiring electrical insulation between turns of the coils, between coil layers, between adjacent coils, and between coils and associated parts such as the magnetic cores and structure.

The coil insulation in high-voltage rotating machines may be subjected to gaseous ionization or corona discharge during proof testing and in service. These partial discharges can occur externally from the windings to the metal frame or cores; and internally in voids or crevices in the insulation. Analyses of electrical failures in high-voltage magnetic devices have revealed erosion in the larger cavities of nonhomogeneous insulation. These

larger cavities may have initially developed by thermal aging, mechanical forces, or by partial discharge attack. A combination of these degrading effects is most likely.

The erosion or weakening of insulation through internal discharge attack may be the result of several effects progressing simultaneously:

- Thermal degradation caused by local heating from ionization streamers and increased losses in surrounding solid materials;
- Degradation of solid material and reaction with the gas in the cavity;
- Degradation of the gas and reaction with the cavity surfaces;
- Partial breakdown in solid material (treeing).

6.3.1 Encapsulation. Several manufacturers produce epoxy, polyurethane, and silicone dielectric materials which have been used successfully in aerospace magnetic devices. Some of these materials have restrictions; for example, a minimum operating temperature of -20°C. A material in a particular application may have worked well without restrictions, but the same material in a new application may require restrictions. Scotchcast 280 and 281 are examples. In a large transformer wound with AWG 24 wire, filled Scotchcast 281 was found to be the better product. The filler was fine enough to pass through the winding interspaces, completely filling the coil winding which was 25 cm in diameter, 2.5 cm thick, and 10 cm high. The coefficient of thermal expansion of the coils matched that of the Scotchcast 281 and no cracks or voids developed during temperature cycling between -40°C and +85°C.

Another coil, designed for a higher voltage but lower current, was wound with AWG 32 wire, but the inner windings were not totally impregnated with Scotchcast 281, even after a vacuum treatment followed by nitrogen pressurization at five atmospheres. In a redesign the coils were impregnated with Scotchcast 280, and overcoated with Scotchcast 281. This led to difficulties because during the removal from the mold a grease film and dirt were deposited on the Scotchcast 280 by handling. This grease and dirt, where not completely removed, left the two materials poorly bonded, generating cracks and voids which contributed to high partial discharge counts in a subsequent corona

test. Incidentally, controlled introduction of additives between layers of a dielectric is a method of acquiring voids and cracks for testing to confirm theoretical models.

Some insulations will show excellent bonding to glass test tubes for great temperature extremes, but fail when used as a circuit encapsulation. Some materials may separate at the bond when applied to electrical parts; for example, silicone on epoxy materials, and acid-based silicone on water-based silicones. Occasionally a material will not harden when in a sealed evacuated container. Materials also may have bonding problems when subjected to thermal cycling; that is, the insulation will crack or delaminate when cooled to temperatures less than -20°C. Table 28 shows low-temperature performance of some of the dielectrics that are useful for magnetic devices.[121]

TABLE 28

PERFORMANCE OF INSULATING MATERIALS AT LOW TEMPERATURES AND 10^{-4} N/cm^2 PRESSURE

Material	Voltage	Temperature	Comments
Conap 2521	3000 Vrms	-125 to -125	No damage -
Solithane 113/300 Formula 12	15 KV	-40 to 85°C	Successful
Scotchcast 280/281	3000 Vrms	-40 to 125°C	Successful for Transformers
RTV 615	20 KV	-55 to 85°C	Successful
6154	15 KV	-20 to 85°C	Successful
Silastic E	20 KV	-55 to 85°C	Successful
	3 rms	-55 to 125°C	Successful
Silgan H622	3 kVrms	-55 C to125°C	Successful
Stycast 2651	3kVrms	-55°C to 125°C	Successful

121. W. G. Dunbar, "High Voltage Power Supply Materials Evaluation", 1982, IEEE International Symposium on Electrical Insulation, 82CH1780-6-EI, June 1982, pp 46-50.

Insulations used for encapsulation and conformal coatings should be applied and then vacuum-pressurized. The coil should be properly cleaned beforehand, the encapsulant outgassed and poured into the mold containing the coil, and the encapsulated coil evacuated until bubbling ceases, followed by 2 to 3 atmospheres of pressurization. The pressurization will usually seal insulated wires by driving the encapsulant into the wire strands at the end of the wire. It will also force insulation into small intraspacial voids in the coils. X-rays may be used to verify large voids between high-voltage windings and grounded surfaces.

The electrical properties of some epoxies, silicones, and polyurethanes, having high service temperatures and good dielectric strengths are listed in Table 29. A more complete listing of the thermal, mechanical, and chemical properties of Scotchcast 281 epoxy is shown in Table 30. A listing of many materials used for encapsulating equipment can be found in Reference 122.

6.3.2 Terminal Boards and Supports. Composite and laminated insulation is used for terminal boards, and also for supports that separate the coils and wiring from the cores, structure, and containers. Some electrical and mechanical properties of glass and nylon containing laminates are shown in Table 31 A more complete list of materials and properties can be found in References 122 and 123.

A terminal board for high potential should be made from qualified insulation. The board may be flat, if the voltage is less than 20 kV, provided the electrical stress is:

Less than 10 volts/mil for long life (10-30 years)

Less than 10-25 volts/mil for short life (1 month to 1 year)

with treated boards in a dry, clean, atmosphere of pure gas these values can be increased 3 times the above value.

122 J.F. Sutton and J.E. Stern, "Spacecraft High-Voltage Power Supply Construction," NASA Tech. Note., NASA TN D-7948, Goddard Spacecraft Center, Greenbelt, Md., April, 1975

123 H.L.Saums, and W.W. Pendleton, Materials for Electrical Insulating and Dielectric Functions, Hayden Book Co., Rochelle Park, N.J. 1973, pp 129-155

TABLE 29

AEROSPACE DIELECTRIC MATERIALS

Material	Service Temperature °C	Dielectric Constant	Dielectric Strength V/mm	Volume Resistivity Ohm - cm
		EPOXIES		
XR5192	130	4.62	11,000	$1.5x10^{13}$
Scotchcast 3	130	3.3	12,000	$1x10^{15}$
Scotchcast 235	130	5.2	13,000	$1x10^{15}$
Scotchcast 280	155	4.9	15,000	$1x10^{14}$
Scotchcast 281	155	4.9	15,000	$1x10^{14}$
		SILICONE RUBBER		
RTV-11	204	3.6	20,000	$6x10^{14}$
RTV-60	204	3.7	20,000	$1x3x10^{14}$
RTV-615	204	3.0	20,000	$1.0x10^{15}$
RTV-616	204	3.0	20,000	$1.0x10^{15}$
Sylgard 182	200	2.7	22,000	$2.0x10^{14}$
Sylgard 184	200	2.75	22,000	$1.0x10^{14}$
Sylgard 186	250	3.0	23,000	$2x10^{15}$
		POLYURETHANES		
Solithane 113	121	2.8 - 5.0	13,000 - 20,000	$3x10^{14}$

Terminal boards operating at voltages greater than 20 kV should be contoured to increase the creepage paths. Three basic methods of contouring are:

- Cutting slots (gas filled regions) between the terminals.
- Building barrier strips between the terminals.
- Mounting the terminals on insulated standoffs.

TABLE 30

PROPERTIES OF 3M SCOTCHCAST 281 EPOXY

PROPERTY	VALUE
Coefficient of thermal expansion	1.5×10^{-4} cm/cm^{o}C
Thermal conductivity	1.2×10^{-3} cal/cm-sec^{o}C
Specific gravity	1.43
Water absorption	0.4%(weight) in 1000 hours at 23^{o}C
Shore hardness Number	D65
Service temperature range	-55^{o}C to 155^{o}C
Shelf life (before encapsulation)	12 months
Dielectric constant	4.9 at 100 kHz
Dissipation factor	0.05 at 100 kHz
Dielectric strength	15kV/mm
Volume resistivity	1×10^{14} ohm-cm
Flammability	Self extinguishing
Transparency	Opaque

These three methods are shown in Fig. 58 . A combination of the three methods may be necessary for voltages greater than 100 kV. The slots in a slotted board form creepage paths and flashover barriers on both sides of the board. A board with barriers is the most difficult to design. The barriers must be built on both sides of the board, and the board has to be made from materials that will not form creepage paths under the barriers, or in laminated boards, through the board laminates. The barriers must not interfere with the terminals or the wiring.

TABLE 31

PROPERTIES OF LAMINATES AND COMPOSITIONS

Material Properties

NEMA Grade	Base Material	Resin	Specific Gravity	Water % absorbtion
G-7	Glass cloth	Silicone	1.68	0.55
G-9	Glass cloth	Melamine	1.9	0.8
G-10	Glass cloth	Epoxy	1.75	0.25
G-11	Glass cloth	Epoxy	1.75	0.25
N-1	Nylon	Phenolic	1.15	0.6
FR-4	Glass	Epoxy	1.75	0.25
FR-5	Glass	Epoxy	1.75	0.25

Mechanical Properties

	Flexural Strength $N/m^2 x10^8$ 1.6mm thick	Tensile Strength $N/m^2 x10^8$	Compressive Strength $N/m^2 x10^8$	Bond Strength kg	Rockwell Hardness M-scale
G-7	1.4	1.6	3.1	295	100
G-9	4.1	2.7	4.5	770	--
G-10	4.1	2.4	4.8	900	110
G-11	4.1	2.4	4.8	725	110
N-1	0.7	0.6	1.9	450	105
FR-4	4.1	2.4	4.8	900	110
FR-5	4.1	2.4	4.8	725	110

Electrical Properties

	Dielectric Constant 1 MHz 0.8mm	Dissipation Factor 1MHz 0.8mm	Dielectric Strength Kv/mm (0.8mm)	Resistivity Volume Resistivity OHM-Cm	Resistivity Surface Resistance Megohms	Arc Resistance Sec.
G-7	4.2	0.003	11	--	--	180
G-9	7.5	0.016	10	--	--	180
G-10	5.2	0.025	20	10^{12}	10^4	128
G-11	5.2	0.025	16	10^{12}	10^4	115
N-1	3.9	0.038	15			
FR-4	5.2	0.025	18	10^{12}	10^4	128
FR-5	5.2	0.025	18	10^{12}	10^4	128

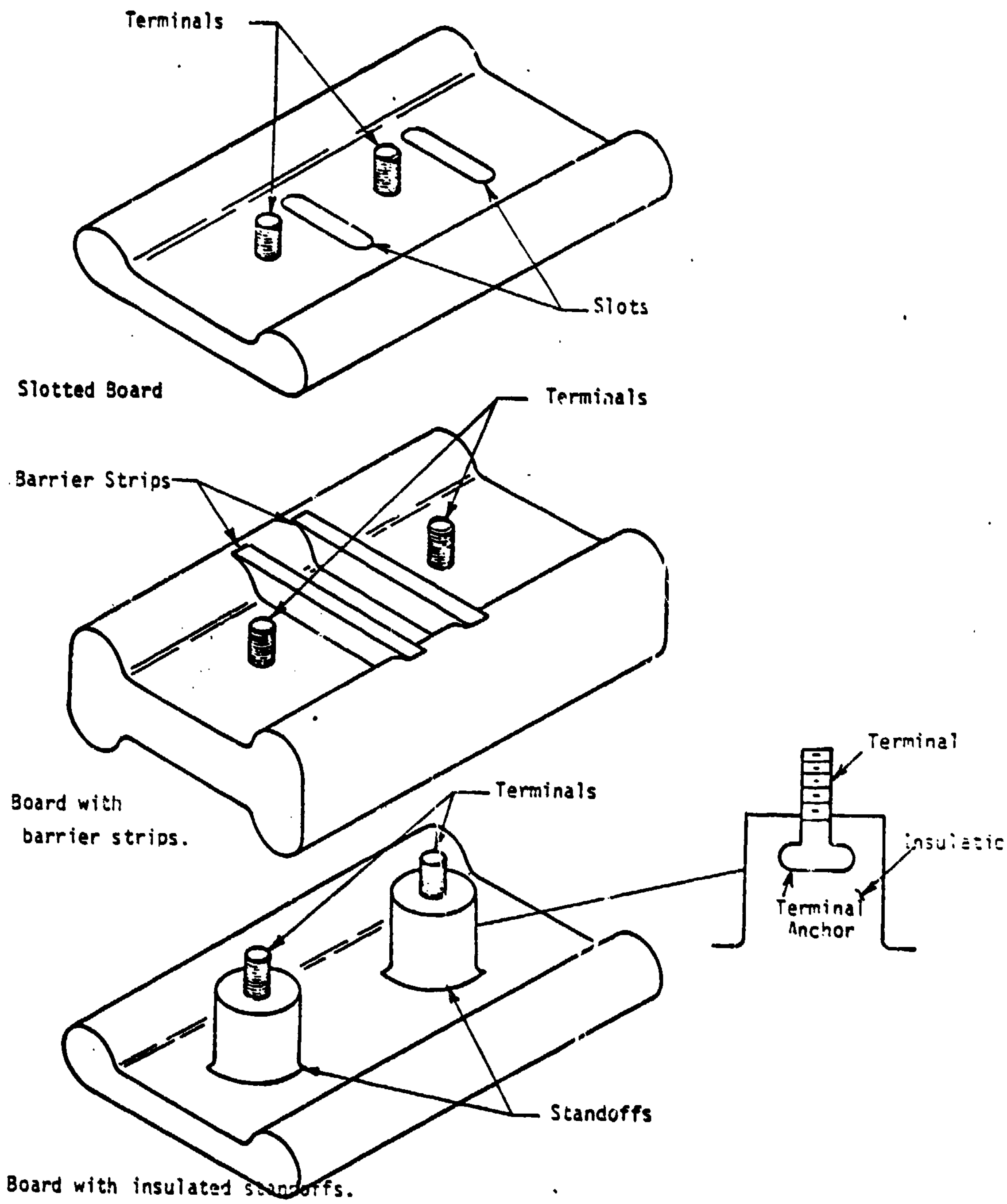


FIGURE 58. TERMINAL BOARDS

Insulated standoffs are a form of the barrier strips. They are difficult to design because they must withstand the forces applied by the terminals, and the terminal anchor must be embedded in the top surface of the standoff. The anchor must be contoured for minimum electrical stress.

6.3.3 High Voltage Leads. Leads between high voltage parts should be made of round, smooth-surfaced polished metal tubing. Steel and nickel-plated metals are preferred, but other softer metals are often used because they are easier to fabricate. The radius of curvature on all bends should be at least 2.5 times the conductor diameter to avoid flattening or crushing the tube at the bend. The ends of the tubes should be flattened as little as possible but this becomes difficult for pieces other than straight sections. When the end of the tubing is flattened the corona suppression shield should extend over the edges and the flattened end of the tubing as shown in Fig. 59. Ample space must be provided between the inside surface of the insulator and the metal tube. A safe design would be based on the assumption that the full voltage stress exists on the top edge of the bushing.

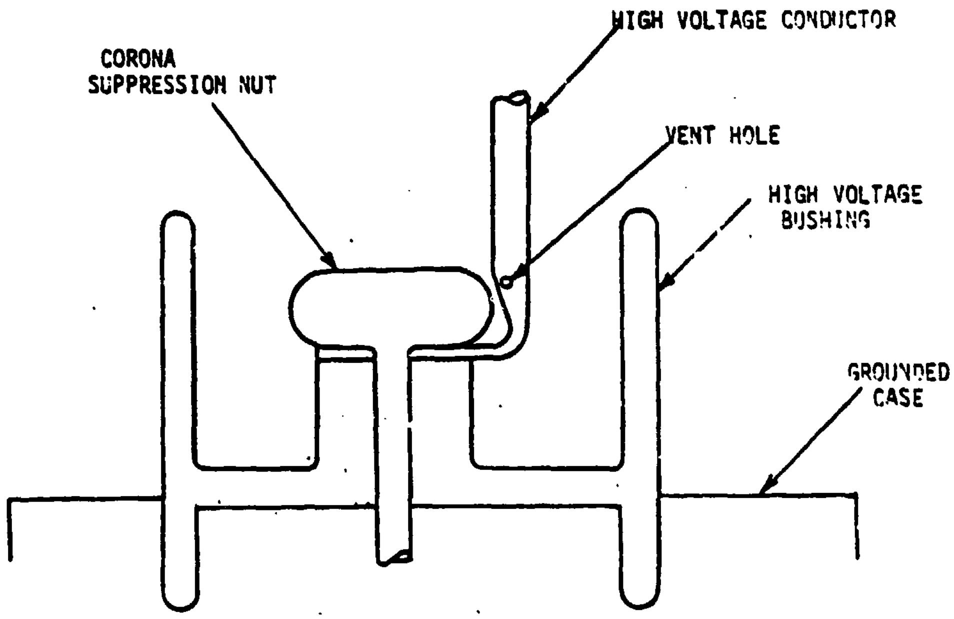


FIGURE 59. HIGH VOLTAGE LEAD AND BUSHING

Hollow tubing must be vented. Vent holes should be drilled through one wall of the tubing at both ends. The vent hole should face the corona shield. No other holes should be drilled in the tubing.

6.3.4 Special Design Features. High voltage flexible lead terminations should be designed to eliminate pressure points on the terminal board (Fig. 60). Pressure points will cause delamination which enhances internal tracking. Also, the terminal should be protected with a corona ball or shield.

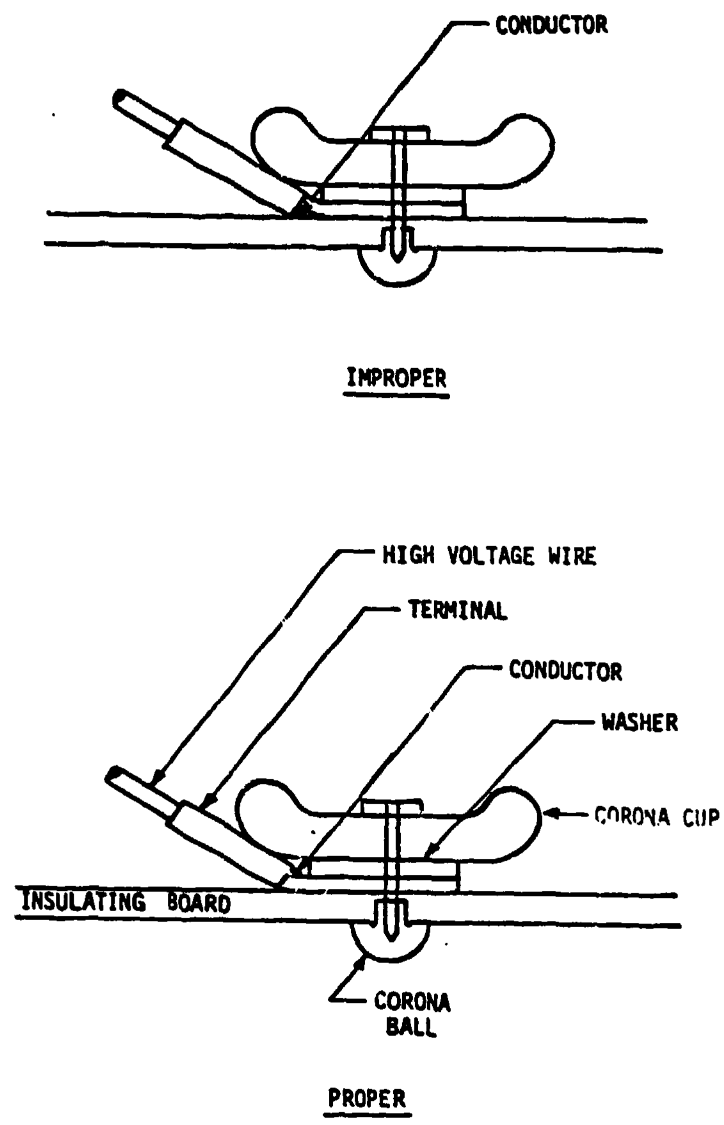


FIGURE 60. HIGH VOLTAGE TERMINALS

Other insulation techniques include either burnishing or enameling over the knots in ties. Otherwise, the feathered ends will become points from which corona discharges will emanate (Fig. 61).

Small pieces of insulation must be cleaned out of the transformer case. Otherwise the "chips" may lodge in the field between a coil and metal, cause corona, which ruins the gas or oil. Wire terminations should be designed and installed so the field approaches that of a parallel plate configuration without point discontinuities.

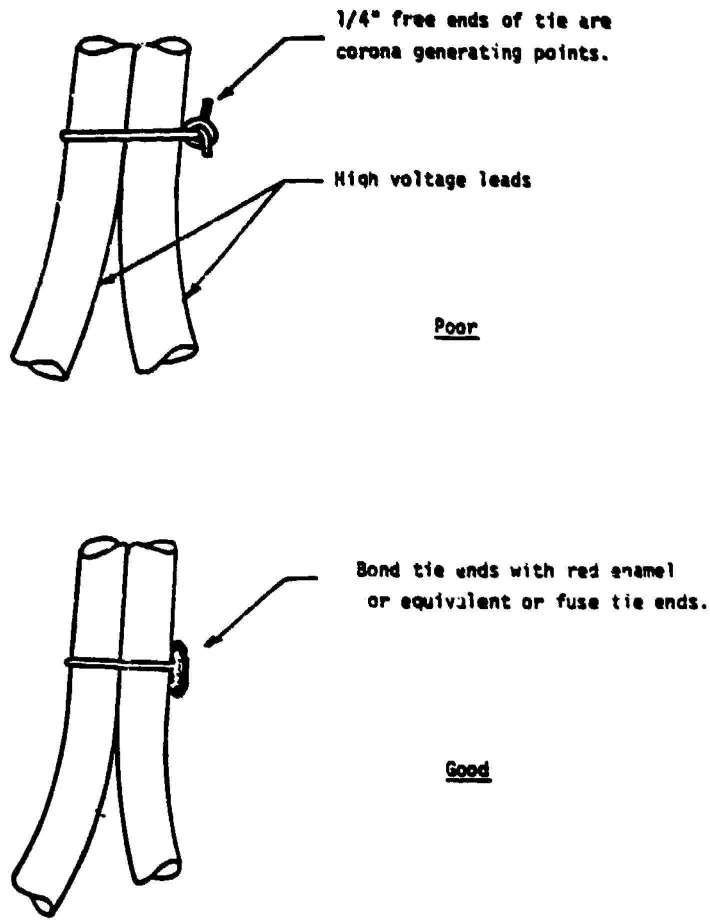


FIGURE 61. HIGH VOLTAGE TIES

Encapsulated coils and the coil supports should have rounded corners (Fig. 62). Rounding the corners eliminates high stress points or low utilization factors in the media between the encapsulated coil and its support, frame, or adjacent coil.

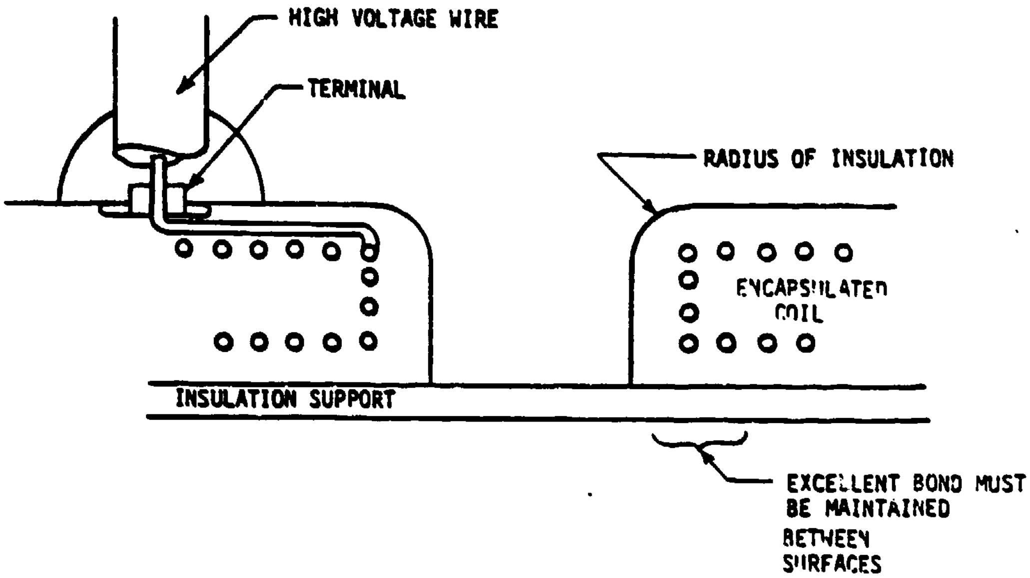


FIGURE 62. ROUND CORNERS ON ENCAPSULATED COILS

6.4 Solid State and Vacuum Parts. Sometimes in aircraft installations, live high voltage circuits must be switched. Devices used to switch aircraft high voltage are hard-vacuum tubes, hydrogen thyratrons, silicon controlled rectifiers (SCR's), and vacuum switches. Associated with these components are resistors, capacitors, wiring, magnetic devices, isolating transformers, or electro-optical isolators, and triggering circuits. A device sometimes used in high voltage circuits is the crowbar, which very quickly shunts the high-voltage conductors with a resistor to harmlessly discharge energy storage capacitors to prevent a damaging dissipation of energy into a fault.

High voltage circuit components protected by a crowbar circuit may be subjected to large voltage transients and excursions preceding and during faults. These transient voltages may be either negative or positive and more than double the normal circuit voltage with high frequency voltage components. The insulating surfaces and thicknesses must be capable of withstanding multiple crowbar actions. Therefore, insulation used in and around these circuits must have a basic insulation level. Boards, terminals, bushings, and other insulation must be impulse tested to show capability for withstanding at least 100 to 500 impulses. See Pulse Testing, paragraph 7.3.3.

The selection of high-voltage switches is beyond the scope of this design manual. The following paragraphs deal with the installation of high-voltage switches and their auxiliaries, and the techniques of making safe and corona-free electrical connections.

6.4.1 <u>Fields</u>. The high voltage insulation design starts with a circuit diagram showing all parts and their voltage levels. The parts are then arranged in a preliminary package which minimizes the voltage between parts and voltage across each part. In designing high voltage assemblies, it is important to avoid crossovers that put a low voltage surface on one part next to a very high voltage surface of another part. Circuits containing resistive of capacitive voltage dividers require careful design, especially if the resistor is long. For instance, a resistor or group of resistors may be a voltage divider between the high voltage terminal and ground. The normal plan is to zig-zag many resistors from the high voltage terminal to the ground terminal, or to have one resistor with one end attached to the high voltage terminal and the other end grounded. Sometimes other high voltage parts near the center of the resistor or resistor chain may be at full voltage or at ground potential, stressing a zone which is not normally designed for voltage stress. This must be avoided.

6.4.2 <u>Taps and Plates</u>. A high voltage rectifier is normally assembled from a series of connected diodes. Occasionally, a voltage tap is required at the center of the diode string. This tap should be made of material having the same diameter as the diode surface, and thick enough for attachment of a round tubular connection. Soldered joints should not

be used because most solder electrodes have lower breakdown potentials than do metals such as steel, nickel, brass, copper, and aluminum.

A potential shaping surface within a stack of series-connected diodes can be a thin plate of metal, provided with a large-radius edge as shown in Fig. 63. This curved edge suppresses corona.

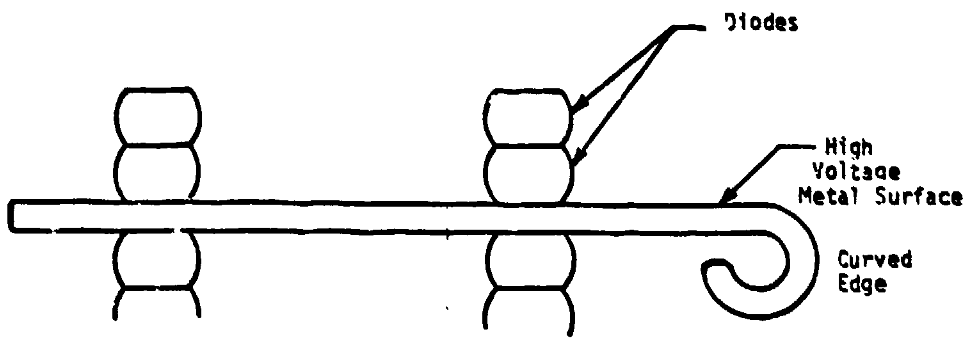


FIGURE 63. CURVED EDGE ON HIGH VOLTAGE PLATE

6.4.3 Control Wiring. High voltage units may use circulating pressurized gas for part of the insulation system, and also for cooling parts.

Electrically controlled switches may also be required for system voltage regulation and performance measurement. These functions are done with components such as fan motors, relays, motor-driven switches, and instrumentation, sensors and circuits, operating at voltages less than 250 volts rms or dc. These devices and circuits as normally insulated are incapable of withstanding the induced transient voltages coupled into them by high voltage faults, crowbar action, and the high voltage start-stop sequences. Therefore, these circuits and their wiring must be shielded.

Low voltage devices and their wiring must be kept away from the high voltage circuits. Low voltage conductor shielding has rough surfaces which

look like multiple points that enhance field gradients with respect to the high voltage, lowering the breakdown voltage between high voltage parts or conductors to the low voltage shields.

Shielding the low voltage components and wiring should be adequate to hold the induced impulses to less than 750 volts peak in common-mode and differential-mode circuits, and to less than 7500 volts peak in the wiring. These limits will prevent destruction of most hardened solid state devices, inductors, capacitors, and resistors used in the control circuits. Many circuits have been evaluated for damage or malfunction by electromagnetic pulses. Some of these data were compiled in Reference 124.

6.4.4 <u>Insulated High Voltage Wiring</u>. A designer may have to interconnect two or more components with a high voltage flexible wire which has insulation inadequate to sustain the full electrical stress of the applied voltage. He can do this if he:

(1) Increases the diameter of the wire with more insulation. With dc voltage stress, the low resistance of the insulation and near infinite resistance of the gas, will allow the surface of the wire insulation to charge to the conductor voltage level. This larger diameter will lower the voltage gradient in the highly stressed gas next to the conductor. With ac, the voltage at the surface of the wire will be determined by the configuration and dielectric constants of the wire insulation and gas space.

(2) Provides adequate and rigidly controlled spacing between the wire and ground planes.

Generally, extra-flexible wire should be used only when the bending and intertwining of the tubing through the high voltage volumes is too difficult

124. ---"Component Damage/Malfunction Levels," Technical Memorandum, TM-75, Prepared for U.S.Army Engineering Division, Huntsville, Corps of Engineers, Contract DACA87-72-C-0002, Submitted by Boeing Aerospace Company, Seattle, Washington, December 1974

or will mechanically stress parts during installation. Terminations on extra-flexible wire will not stay in place as they will with solid tubing. Therefore, the terminations must either be keyed to a slot in the insulation barrier, or a special locking device must be developed for the termination and/or wire end.

7. TESTS

High voltage insulation is tested to evaluate its physical and electrical properties and to predict its service life. Equipment tests should be designed to verify the quality of the insulation rather than to serve as a failure analysis tool.

7.1 Insulation Tests. There are two categories of insulation testing: 1) material evaluation and 2) component insulation tests.

Material evaluation tests include tests of the electrical and physical properties. Electrical properties are dielectric strength, dielectric constant, dissipation factor, surface resistivity, volume resistivity, surface resistance, and life at pertinent temperatures. Physical properties include flexural strength, tensile strength, wrap and twist, water absorption, linear and bulk coefficient of thermal expansion, heat capacity, chemical resistance, and flammability. Materials are usually evaluated in commercial testing laboratories and in laboratories operated by manufacturers of insulation.

Component evaluation tests which are designed to evaluate insulation integrity and life, involve measurement of 1) insulation resistance, 2) dielectric withstanding voltage (DWV), 3) basic insulation level/Pulse and 4) corona. Insulation resistance and DWV tests are mandatory, BIL and corona tests are desirable.

7.2 Materials Testing. An accepted standard electrical insulation code, by defining nomenclature and test requirements for the high voltage insulating materials, would enable the design engineer to establish test hardware quantity, test parameters, and needed test equipment. Such a code does not exist in a form satisfactory for aircraft work. The best thing the designer can do is to adapt ASTM, IEEE, and NEMA high voltage testing standards to his aircraft application.

The following sequence of testing will prevent a high potential from being applied to the insulation which may not be in suitable condition for such a test:

1. Visual inspection
2. Insulation resistance measurements
   - Volume resistivity
   - Surface resistivity
3. High potential applied to solid insulation between two metal electrodes.
4. Tracking
5. Final insulation resistance measurement
6. Life test

Electrical insulation when received should be inspected to confirm dimensions and to find any flaws, hidden moisture, dirt or other contaminants. Its insulation resistance should be measured and it should be subjected to a high potential test, to measure leakage.

ASTM Tests. Present ASTM standard tests do not impose all the operating-environmental conditions on airborne equipment. Therefore ASTM tests should be modified by adding the altitude environment and a time-temperature schedule. ASTM high potential tests for terrestrial equipment are not completely applicable to airborne equipment, but are useful for detecting insulation flaws and incipient failures which will show up after the insulation ages.

Electrical properties of insulating materials should be measured in accordance with the test methods in Table 32. Electrical insulation when received should be inspected to confirm dimensions and to find any hidden moisture, dirt or other contaminates. The insulation resistance should be measured, and then the insulation should be subjected to a high potential test to measure leakage current.

7.3 Component and Equipment Tests. The purpose of testing components and equipment is to determine their flightworthiness. The suggested order for these tests is: insulation resistance, Partial Discharge (PD-1), high potential ,

TABLE 32

TESTS OF ELECTRICAL PROPERTIES OF INSULATION

TESTED PROPERTY	TEST CONDITION	EVALUATED	TEST METHOD
Dielectric Strength	DC/AC 1/4" Electrodes	When received and following environmental stress	ASTM, D-149-61 (Modified)
Tracking	DC/AC	Following environmental stress	ASTM D-495 or ASTM D-2302
Dielectric Constant	1 Kilohertz	When received	ASTM, D-150-59T
Dissipation Factor	1 Kilohertz	When received	ASTM, D-150-59T
Volume Resistivity	125 volts	When received and following environmental stress	ASTM, D-257-61 (Modified)
Surface Resistivity	DC	When received and following environmental stress	ASTM, D-257-61 (Modified)
Insulation Resistance	DC	Following enrironmental stress	Based on 0.05 mfd wound parallel-plate capacitor
Life	DC/AC	Vacuum (Plasma)	ASTM, D2304-64T (Modified)

(DWV), Pulse, and PD-2. Partial discharge test instruments are usually referred to as corona test sets.

7.3.1 Insulation Resistance. Insulation resistance is tested by applying across the insulation a low voltage, like 50 to 100 volts dc. An instrument sensitive enough to detect picoamperes measures the resulting current, and the insulation resistance is calculated with Ohm's law.

Insulation resistance should be measured prior to high potential tests to avoid unnecessary failures from defective, damp or dirty insulation. High insulation resistance by itself does not prove that the insulation of a component does not have cracks or other faults where insulation breakdown may subsequently start. Therefore, an insulation resistance test is not a substitute for high potential tests, which should follow an acceptable insulation resistance test.

Insulation resistance should also be measured after high potential tests because insulation damage from a high potential breakdown may otherwise be difficult to detect. Lower insulation resistance after a high potential test indicates a failure. Obviously, insulation resistance must be measured both times at the same temperature.

The test current during measurement of insulation resistance should be limited to 5 milliamperes with the voltage source shorted. Most "Megger" instruments limit direct current output to 4 milliamperes or less. This limitation avoids unnecessary heating of the insulation at the leakage paths if the insulation resistance is low. Insulation resistance that is low because of moisture can usually be restored by baking.

7.3.2 High Potential Test. In a high potential test the intentional grounds of the component being tested are disconnected, and the voltage is applied between mutually insulated elements of the electric equipment and between insulated elements and the frame or "ground." For example, in a three phase Y-connected alternator the windings would be ungrounded at the common point. Normally, the test voltage should not appear across solid-state devices.

A common test voltage for 28-volt and 120-volt equipment is two times normal plus 1000 volts. Some airborne equipment is tested with lower voltage, especially if short-life and dense-packaging is involved. Sometimes this equipment is designed with a DWV that is less than 160 percent of the operating voltage, it should be at least 160 percent for quality hardware.

High potential tests are designed to electrically stress high voltage components and equipment, but with safety margins sufficient to protect the equipment from damage or malfunction. The basic damage/malfunction mechanism for components and equipments relates to the DWV. Parts with similar and/or identical electrical insulation should have similar or identical DWV.

High potential tests are intended to detect insulation flaws, discontinuities, aging cracks, and deteriorated or inferior insulation. A hole or crack in insulation, through which an inductive surge voltage will discharge and ultimately "carbonize a conductive path, may be detected by a high-potential test if the test voltage is high enough. Test voltages under 1000 volts rms are too low.

The high potential should be applied for 60 seconds. Repeated application of high potential test voltages can reduce the dielectric strength of insulation. Whether any significant reduction in dielectric strength occurs depends on the number of tests, the insulation material, and the insulation thickness. Up to ten high potential tests would probably not permanently damage the insulation.

Some systems have large voltage-transients generated by rectifiers or mechanical switches. The DWV test must exceed the highest of these transients by at least 20%. Each application must be assessed on the basis of required operating life and operating conditions.

7.3.3 Pulse Tests. Pulse or basic insulation level (BIL) tests are required for components and equipment which will be used where electromagnetic pulses (EMP) or switching surges are expected. A BIL test subjects the insulation to a voltage pulse having a rise time of about one microsecond.

High voltage public utility apparatus is specified to meet lightning and transient insulation standards, in addition to the dielectric withstanding voltage requirements. These transient requirements are referred to as the basic insulation level (BIL) for the insulation system. The BIL is based on a pulse with slower rise and longer duration than an EMP. Thus, using the BIL is a conservative approach to designing electrical insulation for fast EMP transients. The slowest EMP transients are essentially the same as the BIL standard transient.

Basic insulation levels were defined during the joint January 1941 meeting of AIEE-EEI and NEMA Committees. This group adopted the basic insulation levels in terms of pulse voltages according to the following definition:

> "Basic impulse insulation levels are reference levels expressed as impulse crest voltage with a standard wave no longer than 1.2 x 50 microseconds (1.2 microseconds rise to 0.90 peak voltage and 50 microseconds decay to 0.5 peak voltage) (see Figure 64). Apparatus insulation as demonstrated by suitable tests shall have capability equal to, or greater than, the basic insulation level."

The above requires that equipment/components conforming to the definition shall have a pulse test value not less than the kilovolt magnitude entitled basic insulation level (BIL). Also, equipment/components conforming to these requirements, with a few exceptions for solid-state devices, should be capable of withstanding the specified voltage, whether the pulse is positive or negative in polarity. Standard atmospheric conditions are assumed.

The joint IEEE-EEI and NEMA committees have agreed upon BIL values for high voltage transmission and distribution equipment/components to ensure continuous system operation during and following lightning and transient conditions. The committee has not standardized BIL values for all low voltage and airborne electrical equipments, that is, equipment/components with operating voltages less than 1200 volts rms (1700 volts crest) or equipment/components operating at altitudes above 10,000 feet.

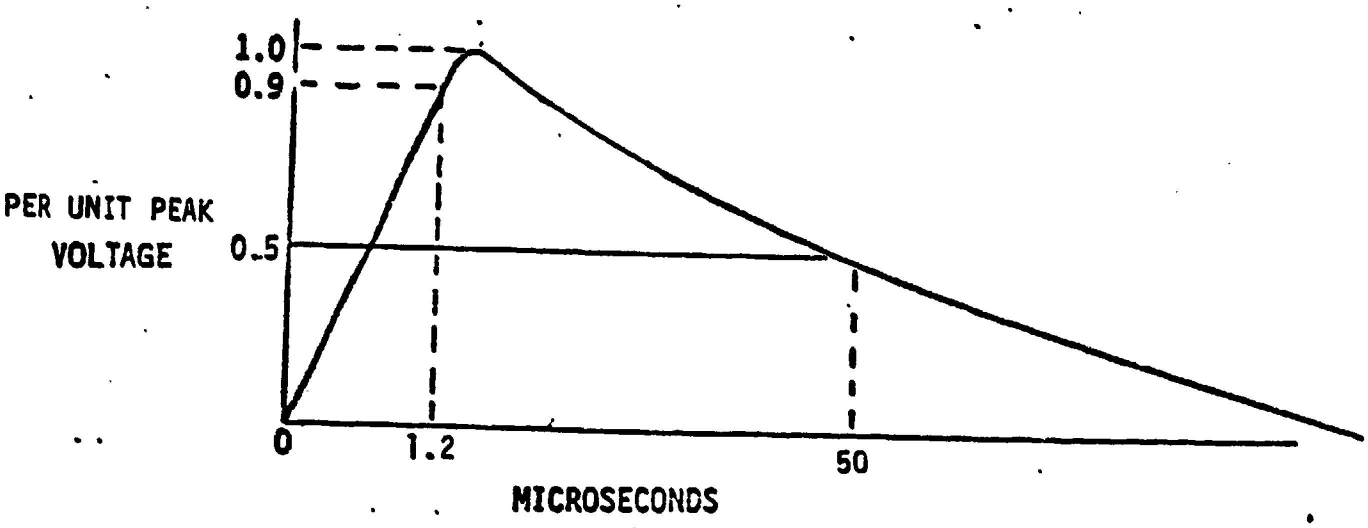


FIGURE 64 . WAVEFORM FOR BASIC INSULATION LEVEL (BIL) DEFINITION

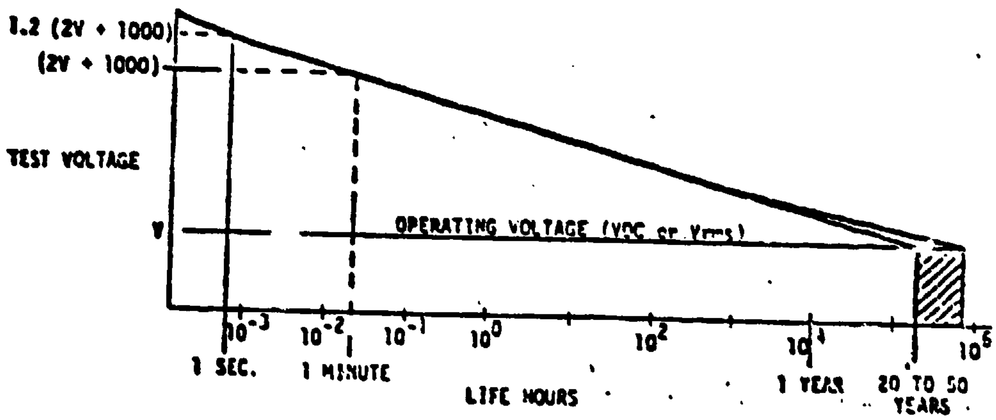


FIGURE 65. DIELECTRIC-WITHSTANDING-VOLTAGE MARGIN
AFFECTS INSULATION LIFE

Insulation is able to withstand higher voltages, within limits, as the test duration becomes shorter (Figure 65). Experiments have shown that insulation will function for 20 to 50 years if its initial 1-minute dielectric withstanding voltage (DWV) is two times the operating voltage plus 1000 volts. Experiments have also shown that the electrical insulation breakdown voltage could be increased 20 percent if the DWV time was decreased from 1 minute to 1 to 5 seconds.

Most experimental work has been with either 50 to 60 Hz ac or steady-state dc. Power industry tests show that the steady-state dc voltage that a given insulation can withstand is higher than the crest value of the ac voltage it can withstand. When a dc voltage is applied the dielectric is charged only once. On the other hand, the recurring charging and discharging with an ac applied voltage heats the dielectric by electrically stressing the molecules in the dielectric. When steady-state dc voltage is applied, the only heating of the dielectric is from current flow through the insulation resistance. Early experiments with insulation showed the dc rating of insulation to be:

$$\text{Rating in volts dc} = (1.7 \text{ to } 2\sqrt{2}) \text{ (ac rating in volts rms)} \quad (5\text{-}1)$$

Factors which decrease the pulse level an insulation can withstand are material aging, power system transients experienced, and the maintenance status of the equipment. Insulation pulse ratings are decreased to the range of 0.75 to 0.85 of their original values by these phenomena.

An insulating material is also degraded by repeated pulses . This degradation is time variant (Figure 66), with less than 10 pulses having little effect on the insulation integrity. The data in Figure 66 implies that the breakdown of insulation proceeds with the growth of pre-breakdown channels created by previous pulsing, a process having three distinct phases: (1) An initial period during which the pulses initiate a pre-breakdown channel, (2) a slow growth of the channel, and (3) a fast growth of the channel. For example, over 10,000 pulses were required for the slow growth of the channel in epoxy insulation for a pin-to-plane configuration, with the pin spaced 5 millimeters from the plane (Ref. 125).

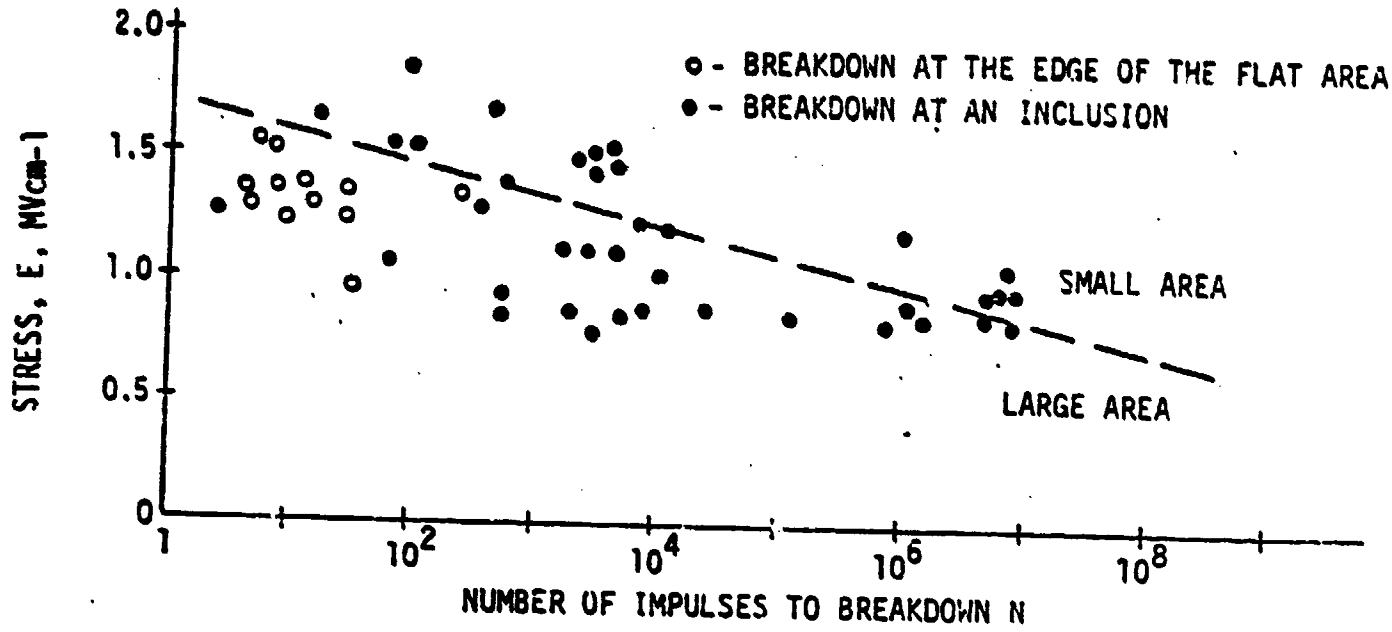


FIGURE 66. RELATION BETWEEN ELECTRICAL STRESS AND NUMBER OF IMPULSES REQUIRED TO PRODUCE BREAKDOWN WITH 1/50 MICROSECOND IMPULSES

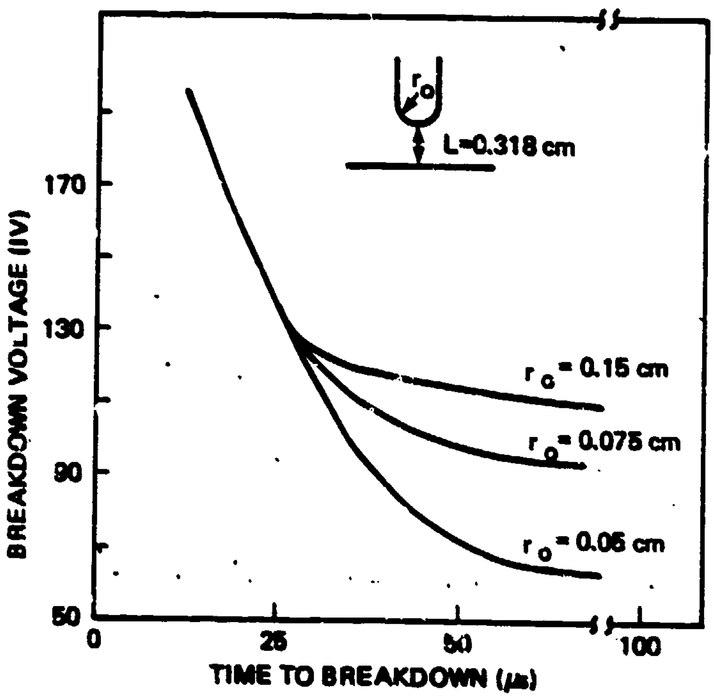


FIGURE 67. TIME TO BREAKDOWN VS. BREAKDOWN VOLTAGE IN TRANSFORMER OIL FOR 100 MICROSECOND RECTANGULAR VOLTAGE PULSES BETWEEN ROD-PLANE ELECTRODES.

Experiments by Rzad, et. al.[126], with a rounded rod of various gap lengths in transformer oil are shown in Figure 67 for 100-microsecond square wave pulses. Increasing the voltage using the 100 microsecond pulse shortens the time to breakdown for a given gap length. For a square wave pulse it was also shown that the breakdown voltage was essentially the same for both polarities. The breakdown in oil becomes linear with gap length versus time for larger gaps.

Another group of experiments were made by Katahoire, et. al.[77] for the breakdown along a cross-linked polyethylene (XLPE) submerged in silicone oil (PDMS) and in silicone oil using a standard 1.5/50 microsecond pulse. The pulse voltage is compared to the breakdown at power frequency (60Hz) for the same electrode configuration in Figures 41 and 68.

Pulse voltages for public utilities are much too high for airborne equipment, where compact packaging requires small bushings and minimum dielectric thicknesses. Although airborne equipment is not normally designed to withstand lightning-induced transients, its pulse test voltages should still be twice the rated voltage as shown in Volume I, High Voltage Testing.

7.3.4 Partial Discharge and Corona Tests. Partial discharge and corona tests are used to seek out insulating material flaws by detecting partial discharges in spaces, cracks, and voids.

The most common insulation imperfections are entrapped gas in voids, cracks within insulation, and insufficient space between an insulated conductor and ground or other insulated parts. For example, a generator coil may have small voids within the insulation, between the active conductors and generator magnetic core, or between the turns of two coils within a slot. High voltage coils in the stator will have air gaps between the surface of the coil and the rotor, and between the end turns and the core.

125) S. Zoledziowski and S. Soar, "Life Curves of Epoxy Resin Under Impulses and the Breakdwon Parameter", IEEE, Transactions on Electrical Insulation, Vol. EI-7, No. 2, June 1972, p. 84-99.

126) S. J. Rzad, J. C. Devins and R. J. Schwabe, "Transient Behavior in Transformer Oils: Prebreakdown and Breakdown Phenomena," IEEE Trans. on Elec. Insulation, Vol. EI-14, No. 6, December 1979, pp 289-296.

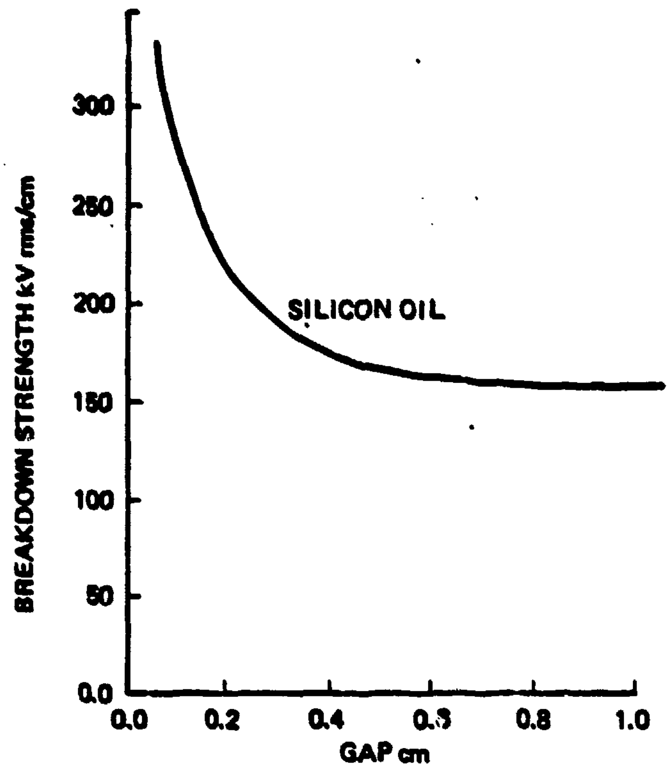


FIGURE 68. POWER FREQUENCY BREAKDOWN STRENGTH OF SILICONE OIL BETWEEN CUP-PLANE ELECTRODES.

Whereas corona is a flow of electrons in a gas surrounding a high voltage element, a partial discharge is a flow of electrons and ions which occurs in a gas over a small volume of the total insulation system. This short duration event emits acoustic, optical, and radio frequency energy. Partial discharges can be detected by measuring any of these radiations (Ref. 126). Although the direct-coupled measurement of the radio frequency current and voltage pulses is by far the most widely employed by industrial organizations other forms of detection do exist. Electronic, sonic, and visual detectors are used to sense and measure partial discharges. These discharges can also be photographed, or observed with photomultipliers. Even their sound has been detected and triangulated to pinpoint the source.

Detectors placed near test articles should not distort the operating characteristics of the test articles or the test equipment. Detectors for use near high-voltage equipment must be sufficiently sensitive so that they can be spaced away from the critical parts of the high-voltage field.

Visual sensors must have sensitivities compatible with the amount of illumination they are to detect. Visible corona can be detected optically on exposed test parts if the test can be operated in darkness. With enclosed equipment, the optical detector must be within the package.

In tests where a solar simulator is used to illuminate the test article, optical corona detection is difficult. Even with shielding, the detection may be difficult except where the detector can be directed toward the part in which the visible corona is expected and sufficiently shielded from ambient illumination.

Gaseous (ozone) detectors are requried to have sensitivities sufficient to detect ozone in the test environments. Because the environment must contain oxygen (and nitrogen produces no ozone) this limits their usefulness. Again, at its spacing from the test article the detector must be sensitive enough to detect the ozone. Requirements of electrostatic detection systems are that they be sufficiently sensitive to be placed a convenient distance from the test article and that the circuitry and readout equipment distringuish the corona, a partial discharge, signal from background noise. The long lead to the readout equipment makes this a difficult requirement to fulfill.

Detector concepts that are capable of detecting corona and partial discharges are described in Table 33, however, no one detector can measure all of the phenomena.

Table 33. Corona Detection Categories

Category	Types	Application	Comments
Light Sources	o Solar cells o Photomultiplier o Cameras o Television cameras o Solid-stage detectors	o Measures light generated by the gaseous ionization between the open electrodes in a darkened chamber	o Sensitive to stray light o Mobile o Cannot measure discharge in voids or enclosures
Mechanical	o Accelerometer o Ultrasonic	o Measures mechnical vibration set up by gas pressure shock waves	o Massive discharges o Subject to external noise sources o Light insensitive o Light, temperature, and pressure insensitive
Electromagnetic radiation	o Voltage standing wave ratio o Antennas o Electrometer o SATO probe o Capacitor probe	o Measures radio frequency emanations generated by the gaseous discharge o Mobile	o Light, temperature, and pressure insensitive o Sensitive to outside radio-impulses o Semidirectional o Unattached to the test article
Electronic pickups	o Capacitor coupling o Attached RF coils o Series resistors	o Measures the high-frequency voltage and current impulses generated by the corona partial discharges	o Attached to the corona-sensitive circuit o Immobile o Light, temperature, and pressure insensitive

Table 33. Corona Detection Categories (continued)

Category	Types	Application	Comments
Chemical detectors (gaseous)	o Mass spectrometer	o Measures generated ozone and out-gassing products	o Must be located close to the discharge o High voltage power supply required o Nondirectional
Scientific instruments	o Geiger counter o Curved plate analyzer o Solid-state detectors	o Measures charged particles radiated by the corona discharge	o Located near the discharge o Mobile o High cost o Requires special modification and instrumentation

Capacitance-coupled detectors are recommended for attachment to specific circuits. These detectors have excellent response, and are easily installed. The radio frequency coupling loop is recommended because it can be moved about to pick up extraneous generated noise. For very large equipment, an antenna or electrometer is recommended. These detectors are lightweight, easily mounted, and insensitive to light and heat.

Coupling loops and direct-coupled capacitors are used in many test circuits. These devices are small, easily installed, and in the case of the coupling loop, can be moved from place to place on the test article. A direct-coupled capacitor is typically used in a simple circuit such as a voltage multiplier in a voltage divider. The capacitor can be connected to one of the low-voltage devices, and the signal fed into a detection circuit. For more complex circuits such as power supplies, electronic circuits, large pulse modulators, or scientific experiments, a radio frequency coupling or direct coupled capacitor is recommended.

With electronic detectors, both the partial-discharge initiation voltage and the extinction voltage are usually measured. The waveform of the partial-discharge pulse is observed to determine the magnitude and type of discharge. The variation in the number and sequence of pulse heights as a function of voltage and time can be measured, and hte pulse energy can be derived from the voltage waveform. From such observations, important insulation characteristics are established, including maximum acceptable operating voltage, quality of insulating materials, quality of insulation design, insulating materials life potential, and type and size of voids and cracks.

Not enough is known about partial discharges and their effect on materials for their measurement to be the only criterion for insulation life assessment for a given applied voltage. Other tools such as high potential testing, testing, dielectric stress calculation, and life testing are required for a full assessment.

Partial discharge detectors have been designed and calibrated for commercial testing of high voltage transmission lines, electrical machinery, and for testing small samples of dielectric gases and materials. During test, these detectors are directly or indirectly coupled to the test article. These directly coupled detectors, unless modified, are unsuitable for vacuum testing.

The output of the detector must be processed to extract the partial-discharge signature from the noise. A refined bridge circuit that nulls out transients generated in the power supply is shown in Figure 69. For precise measurements a pulse-height

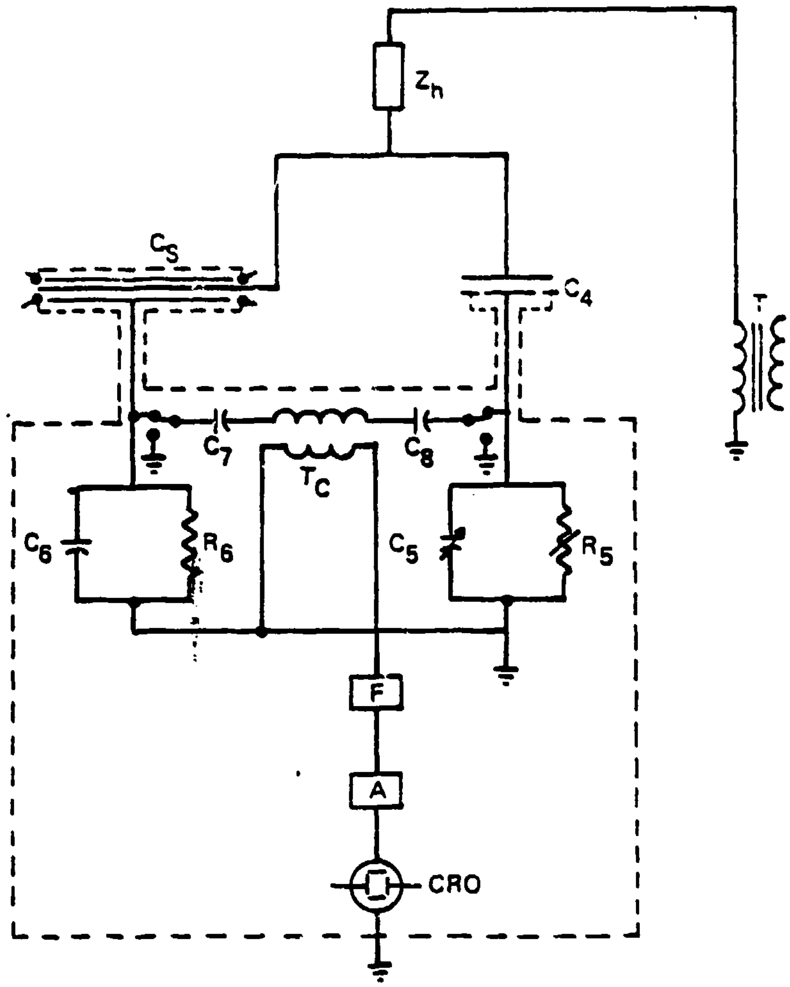


FIGURE 69. BRIDGE DETECTOR CIRCUIT

T	–	HIGH VOLTAGE TRANSFORMER
Z_h	–	SEPARATING IMPEDANCE (MINIMUM INDUCTANCE 0.1 H)
C_S	–	CAPACITANCE OF TEST ARTICLE (1000 to 4000 PF)
C_4	–	COUPLING CAPACITANCE (1,500 TO 3,000 pF)
C_5	–	VARIABLE LOW VOLTAGE CAPACITANCE (0 TO 10,000 pF)
C_6	–	LOW VOLTAGE CAPACITANCE (1,000 TO 3,000 pF)
C_7, C_8	–	FILTERING CAPACITANCE (1,000 pF)
R_5	–	VARIABLE RESISTANCE (0 TO 100,000 OHMS)
R_6	–	RESISTANCE (200 TO 1,000 OHMS)
T_c	–	COUPLING TRANSFORMER (INDUCTANCE OF WHICH IS CHOSEN SO TO OBTAIN OSCILLATION FREQUENCY 15 TO 30 KC/S)
F	–	BAND PASS FILTER (PASS BAND 10 TO 50 KHZ)
A	–	AMPLIFIER
CRO	-	OSCILLOSCOPE

analyzer is used with detection circuits for permanent recording of test data and for evaluating degradation of materials (Figure 70).

The detection impedance to the detector input is usually an RLC circuit having a large impedance to a certain frequency band in the PD spectrum, which causes a signal that can be amplified and displayed on an oscilloscope screen. Most commercial detection systems use one of two forms of detection impedance. The "narrow-band" impedance has a bandwidth of about 10 kHz, centered between 20 and 30 kHz. The "wide band" detection has a bandwidth of about 100 kHz with a center frequency between 200 and 300 kHz. In both cases, the output of the pulse amplifier is relatively easy to observe, even on older models of cathode ray tubes. The pulse output is usually displayed with respect to the power frequency voltage to aid discrimination between PD and electrical noise.

Recently, ultra-wide band (1GHz) amplifier and real-time oscilloscopes have been developed which permit the direct observation of low repetition rate pulses of 1 ns or less duration (Ref. 127). Therefore, with properly designed ultra-wide bandwidth coupling systems (100 kHz to 1 GHz) detection of partial discharges is possible. These ultra- wide bandwidth detection systems are schematically the same as the system shown in Figure 70 except the separation filter and detection impedance Z must be implemented as part of a transmission line to obtain good frequency response.

The advantage of the ultra-wide bandwidth detection system is that a more accurate observation of the true shape of a partial discharge current pulse, rather than the integral of this pulse (the charge) can be observed. In addition, with the use of two or more coupling capacitors on a test article, the sites of partial discharges can be located to within a small area by measuring the times of arrival of pulses at each coupler. Last, the ultra-wide bandwidth system facilitates discrimination between partial discharges and electrical noise (Ref. 128), without isolating the ground of the equipment under test with substantial higher sensitivity advantages in some situations.

127) S. A. Boggs and G. C. Stone, "Fundamental Limitations in the Measurement of Corona and Partial Discharges", IEEE, Trans. on Electrical Insulation, Vol. E.I. -17, No. 2, April 1982, pp 143-150.

128) M. Kurtz and G. C. Stone, "In-Service Partial Discharge Testing of Generator Insulation", IEEE, Trans. on Electrical Insulation, E.I.-14, April 1979, p. 94.

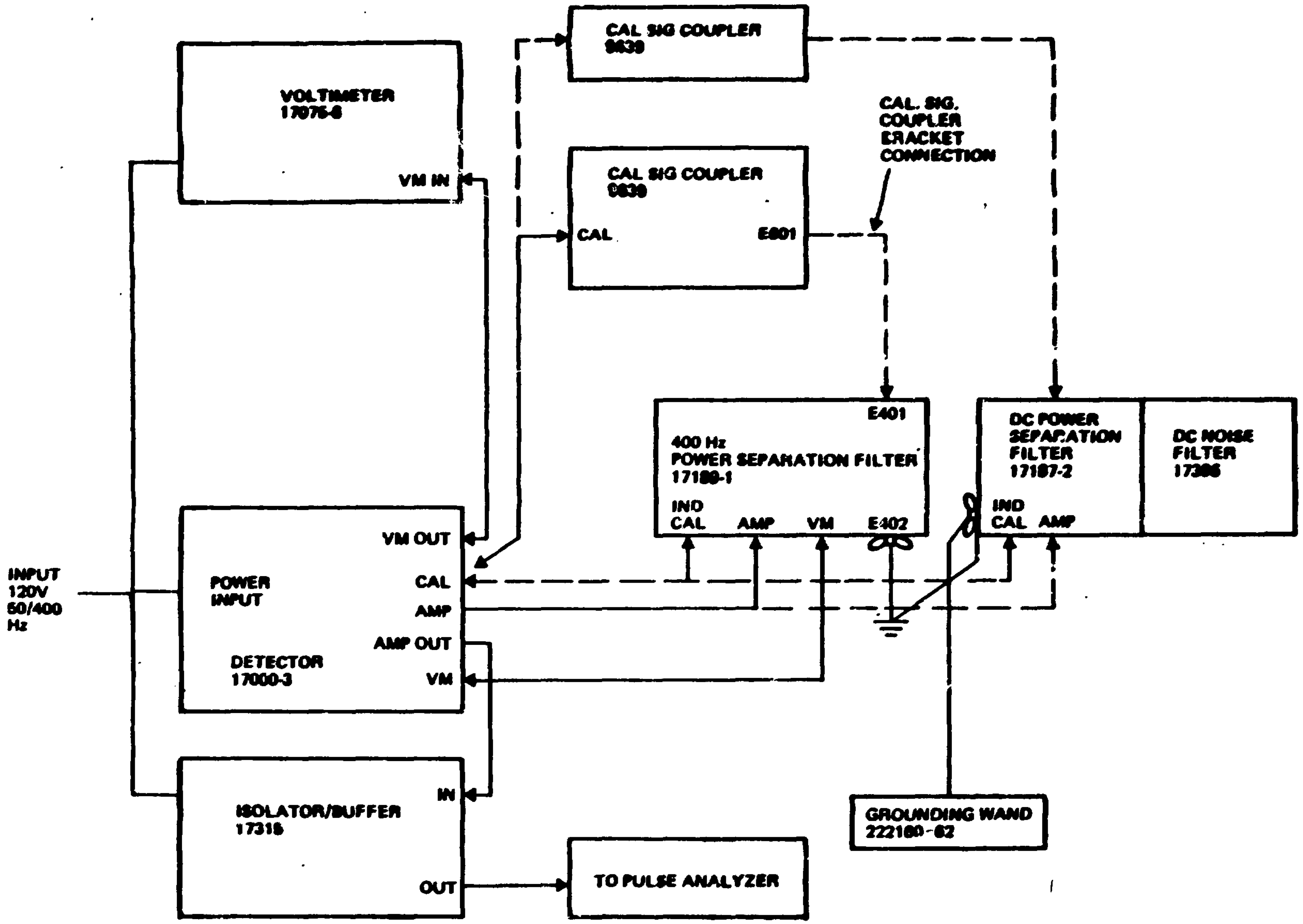


FIGURE 70 : CORONA TEST SYSTEM SCHEMATIC

Frequency, Waveform and Interference. Assessing the effects of frequency and waveform requires careful instrumentation. Most commercial detectors, as recommended by the ASTM D9.12.12, Section L, Committee on Corona, are designed to operate with either dc or sinsusoidal ac, with 50 and 60 Hz ac frequencies preferred. Only recently, (January 1976) did J.G. Biddle Company make a 400 Hz detector and readout which has been needed for many years. Most investigators working with corona and partial discharges have tested, when possible, with 50 or 60 Hz, and extrapolated the resulting data to 400 Hz. When testing dc-to-dc converters having frequencies from 1000 Hz to 50 KHz, detection equipment must be modified to accomodate these frequencies.

With square waves, the detector will pick up the leading and trailing fronts of each wave and display them as very large pulses which look like partial discharges having hundreds of picocoulombs of energy. These pulses will, of course, have to be separated from true partial discharge pulses in the subsequent processing. An oscilloscope, if used, must be kept from becoming overdriven. The detector signal from the bridge is normally amplified by a high frequency amplifier and displayed on the cathode ray tube. Appropriate phasing of the oscilloscope trigger signal with the power frequency, or Z-axis modulation, can be used to blank out the leading-edge from the oscilloscope display.

Signals having a charge of less than one picocoulomb should be measured in a low-EMI screen room. High frequency partial discharge signals of less than one microvolt amplitude are easily lost when the background includes interferring signals of several microvolts. The power supply should be appropriately isolated.

Similarity of Partial Discharge and Calibrating Pulse. Valid readings from partial discharge measuring equipment are obtained only if frequency response of the detector and other circuit elements is broad enough to respond adequately to the frequency content of the partial discharges.

As the frequency content of actual pulses may extend into the range of 100 MHz, any corona detector operating over this frequency spectrum can be adequate for corona-level measurements. It is not a corollary, however, that the particular corona detection set may be calibrated by an excitation pulse having a rise time corresponding to a frequency substantially below 100 MHz. Obviously, in the case of a wide band corona detector, an ideal calibration requires that the rise time correspond to at least 100 MHz if the true response to a corona signal is to be simulated.

With modern pulse generators a calibrating pulse can be shaped to be similar to the pulse from a partial discharge. It is coupled into the detection equipment circuit through a standard quartz or vacuum capacitor.

It is important that the detection equipment be calibrated with respect to the test article, rather than just using a general-purpose calibrating technique. For example, capacitor test set-ups require much more sophisticated calibrating procedures than do set-ups having transformers and inductors because capacitors tend to attenuate their internal partial discharges. Resonant circuits should not appear between the calibrating unit and the test article.

Calibration and Partial Discharge Comparison. Partial discharges at high altitude 30 torr have frequency spectrum components up to 100 MHz (Figure 71).[129] The transit time for an avalanche discharge is between 0.3 and 20 nanoseconds, depending upon the voltage, gas, and spacing. This indicates that calibrating with a slow pulse of a few microseconds would not be representative of a partial discharge. For example, in measuring partial discharges within 5 microfarad capacitors, calibration with pulse rise times of 5×10^{-7} seconds produced good correlation with the capacitor partial discharges. When longer rise-time calibrating pulses were used, the calibrating pulse correlated poorly with the partial discharge pulse height.

There are two classes of calibration for commercial partial discharge instruments: indirect and direct.

Indirect Method. The calibrator is connected to the low-voltage side of the power separation filter (Figure 70). The advantage of this method is that the calibration pulse can be displayed during test at low voltage. The disadvantage is that the calibration is subject to erros due to stray impedances due to long lines and the test article.

Direct Method. The calibration circuit is connected directly to the test article high-voltage termination on the power separation filter (Figure 70). This is a more accurate method but the calibration circuit must withstand the test voltage or be repeatedly disconnected.

129) W. G. Dunbar, "High Voltage Connections for Flight Vehicles", National Aerospace and Electronics Conference, Dayton, Ohio, 1974.

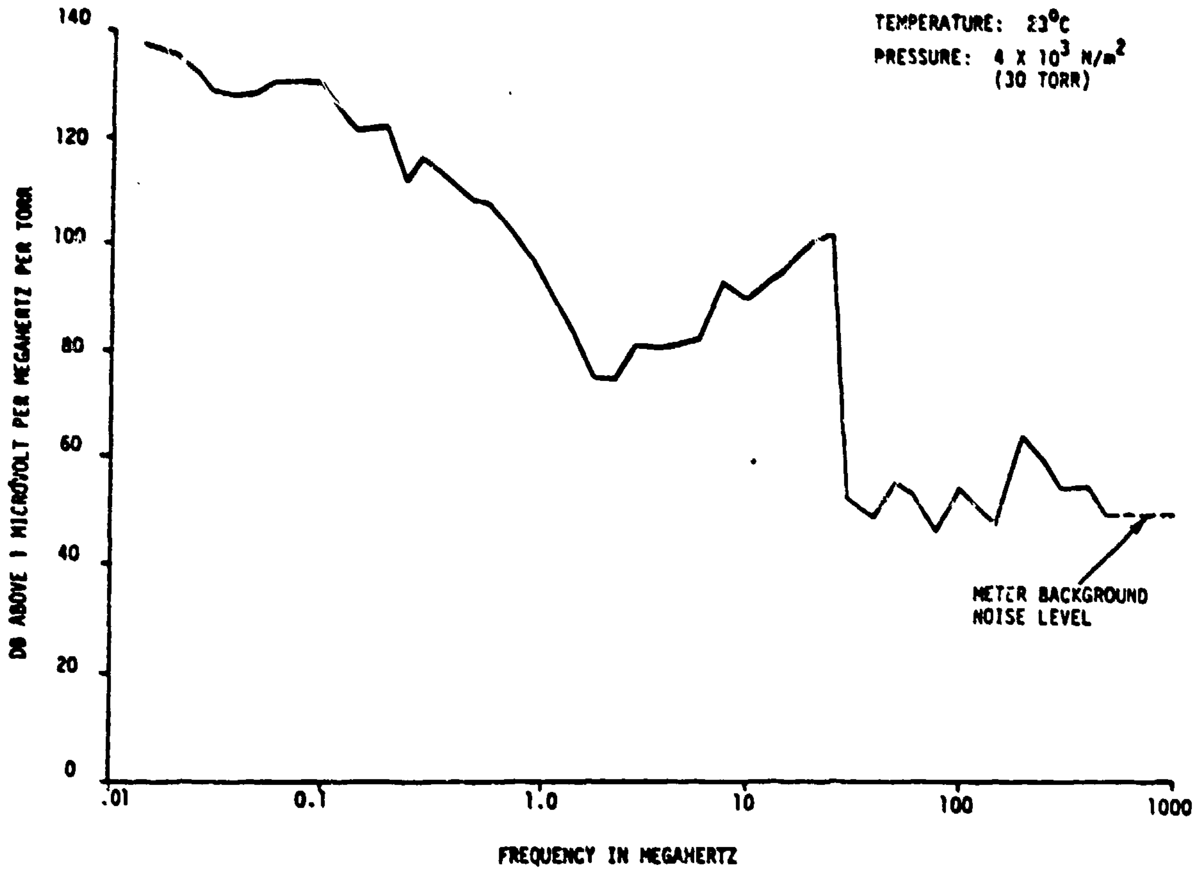


FIGURE 71. FREQUENCY SPECTRUM AT CORONA DISCHARGE

Most commercial detection instruments use a calibration pulse with rise times between 0.1 and 1 microsecond and fall time between 0.1 microsecond and 1.0 millisecond. The advantage of the fast rise time is to obtain a pulse representative of the partial discharge, with the 0.1 microsecond rise time preferred. The fall time should be slower, much slower preferred, than the rise time. If the rise time and fall time are identical, and a pulse height analyzer (PHA) is used in the circuit, two pulses of equal height will appear on the PHA. If the rise time is faster than the fall time, then two pulses will appear with the fall time having lesser magnitude. If the fall time is over 50 times the rise time, then only one pulse will appear (References 130 and 131).

These commercial calibrators have reasonable accuracy. However, many problems with noise, amplifier gain adjustments, and amplifier linearity and system impedance tend to decrease the calibration accuracy. Therefore, acceptable calibration must include the type of calibrator and the calibration method used during the test.

Recommended Measurement System. Of the standard corona test equipment, the bridge detector has the best accuracy, is the most sensitive, and is easily operated. It supersedes the other detectors. Its major limitation is in measurements where square waves and frequencies greater than 60 Hz are used.

Test experience has shown that a universal detector and detector readout instrumentation is yet to be developed. Presently developed systems are designed to the standard D1868 ASTM corona test methods which are adequate for most commercial and 400 Hz sinusoidal power testing.

130) A. S. Ahmed and A. A. Zaky, "Calibration of Partial Discharge Detectors for Pulse Height Distribution Analysis", IEEE, Vol. E.I.-14, No. 5, October 1979, pp. 281-284.

131) R. D. Parker, R. V. DeLong and J. A. Zelik, "Accurate Corona Detector Calibrator", IEEE, Vol. E.I.-15, No. 6, December 1980, pp. 451-454.

7.4 Performance Testing. Destructive and non-destructive tests are used for the qualitative evaluation of electrical/electronic parts and insulation. In the following text, the expression "parts" refers to electrical components such as resistors, capacitors and coils.

7.4.1 Testing and Detection. Generally, the test philosophy for electronic parts and hardware should be that sample flight parts as well as engineering, development, prototype and qualification equipment should be thoroughly and extensively tested and stressed repeatedly to establish the margin of the design. Equipment intended for qualification, should first be tested to acceptance levels to verify workmanship and to identify infant-mortality failure causes. Flight equipment should never be subjected to repeated electrical tests. One test of qualified flight equipment should be sufficient to verify workmanship and expose infant-mortality conditions. Cumulative electrical stress can, on the other hand, jeopardize its operating life.

7.4.2 Equipment Testing. A partial discharge detector probe can usually be located near unshielded equipment; otherwise it is necessary to "build in" the detector. Some devices such as photomultipliers, are good detectors in themselves and require no additional detectors when tested. The normal operating characteristics of items being tested should be thoroughly understood so that off-normal operation can be recognized. Partial discharges, when present, will sometimes be superimposed upon normal waveshapes.

7.4.3 High Voltage Testing. AC high voltage testing is normally conducted to establish voltage endurance as a function of time. AC testing is usually a go/no-go type, with voltage being raised to a specified value with samples that break down within a specified time being rejected.

DC high voltage testing procedures usually differ from ac procedures in that leakage current is measured as voltage is raised. Current varying linearly with voltage indicates the equipment is in good condition. As the breakdown point is approached, the leakage current increases at a higher rate, followed by an avalanche current. With some newer insulations, this knee in the current plot is almost a right angle bend, breakdown being reached about when the first sign of the knee appears. The rate of application of voltage rise also affects the breakdown point.

Reproducible measurements are hard to get in very high-temperature high voltage testing because insulators supporting the equipment and wiring must be cooled to keep them from becoming semiconducting. This creates temperature gradients in the chambers, and even though the gas in the chamber is at constant pressure, its density will vary inversely with its temperature. The partial discharge initiation voltage is affected by gas density, so ambiguities are introduced into the susceptibility of the different parts of the high voltage circuit. Careful design of the test, complete temperature instrumentation, and detailed analysis of test results is required for obtaining valid results.

7.4.4 Parts Tests. A part that is to be evaluated for partial discharges should be completely insulated and placed within the configuration in which it will be in the aircraft. Pre-test processing should include cleaning and potting of parts, and the cleaning and solder-balling of the terminations. For example, if the part is normally on a conformally coated circuit board, then the test article should be assembled in the same way. The spacing between the part and the ground plane should be the same as it will be in the final application. This includes all upper, lower and side ground planes which will limit the field gradients and establish the pressure-spacing dimensions for partial discharges.

The altitude chamber feedthroughs and connections must be free of sharp corners and edges to prevent corona from the high voltage gradients present at such points. There should be no gas pockets or outgassing materials associated with the chamber feedthroughs or connections to the part being tested.

These outgassing parts can create localized zones of higher pressure near the test article, and raises corona initiation voltage for pressure greater than 100 Pa. The test fixture using one of the most important parts of the test must be in its exact position during test installation. All connections and interconnections must be solid, free of outgassing, and corona-free. The best partial discharge detector for testing parts, insulated electrodes, and the gaseous breakdown between fixed electrodes is the bridge corona detector circuit shown in Figure 69. This detector is simple, easily connected, and accurate. However, it has limited sample capacitance range. This is determined by the high voltage coupling capacitor and resonant circuit limitation.

7.4.5 Circuit Tests. Circuits consisting of simple assemblies of parts can be tested in the same way as parts. More complex circuits require special tests or additional detectors. An example of a simple circuit is a voltage divider network or a voltage multiplier. A more complex circuit would be a power supply, a filter circuit, or the high-voltage electronic system.

7.4.6 System Tests. A high voltage circuit within an electrical/electronic system is difficult to test and analyze unless the individual high voltage circuits are instrumented as just described. Often detection devices must be placed as near as possible to the high voltage elements. Applicable detectors for this purpose are RF coils, capacitors, antennas, and ultrasonic detectors.

A typical test circuit and a high-voltage power supply circuit to be tested for corona are shown in Figure 72. The high-pass filter rejects frequencies less than the fifth harmonic of the power supply transformer frequency, thus eliminating much of the noise from the switching devices. However, there will still be noise on the oscilloscope caused by the switching devices and resonant circuits within the test circuit.

Another essential part of the test circuit is the calibration circuit, shown in Figure 73. A second coupling loop is used for this circuit. The calibration loop is placed about 2 inches in from the sensor loop for calibration. Usually a 10 pf capacitor is used for calibration. The square wave signals can be varied from 10 mV to 10 V and the oscilloscope output pulse heights recorded for calibration. This type of sensor must be calibrated before testing commences. The sensor loops are then placed near or on the surface of the test article, as shown in Figure 74, and the electronic circuit tested.

Radio Frequency Coil Detector. The signals shown in Figure 75 were detected with a small (10-mH) coil. The low signal data were recorded using a fiber optic recorder. The large signal sources were recorded with a fiber optic recorder. Corona pulses proved to be at least 10 times greater than signals detected by the fiber optic recorder.

Direct Coupled Capacitor Detector. The signal from a high-voltage discharge circuit is shown in Figure 76. This was detected by a capacitor-coupled circuit. There was a large corona pulse at the top of the pulse (not shown in the photograph) with several pulses in the discharge decay. These discharges were approximately 1 pc in magnitude.

Connection to Low Voltage Resistor. In one instance a computation was made to the low-voltage section of the power-supply voltage divider. This experiment depended upon the charging and discharging of a high voltage capacitor to obtain a voltage-time waveform such as the one shown in Figure 77. When this circuit is operating normally, it is important that the waveform be free of corona discharge; if not, the discharges will appear as data to the scientific observer. In Figure 77, the insulation has voids in the critical high-voltage circuit. Discharges take place during the pulse noise time, and then the voids discharge again during the voltage decay time. These discharges are seen as pulses similar to the scientific data to be observed.

All these detectors will sense external RF electrical noise as well as partial discharge signals, so it is necessary to monitor the power return or common-point ground for noise. This noise, in coincidence circuits is then used to identify and eliminate those observed pulses that are not true partial discharges. Oscillograms of corona and noise signals are shown in Figure 75.

7.5 Facility and Environment. High voltage airborne systems must often be tested in a temperature-controlled vacuum chamber, which of course must be designed to be corona-free. Corona sources that have been encountered in environmental test chambers include:

a. Pressure gauges
b. Heater panels
c. Light sources

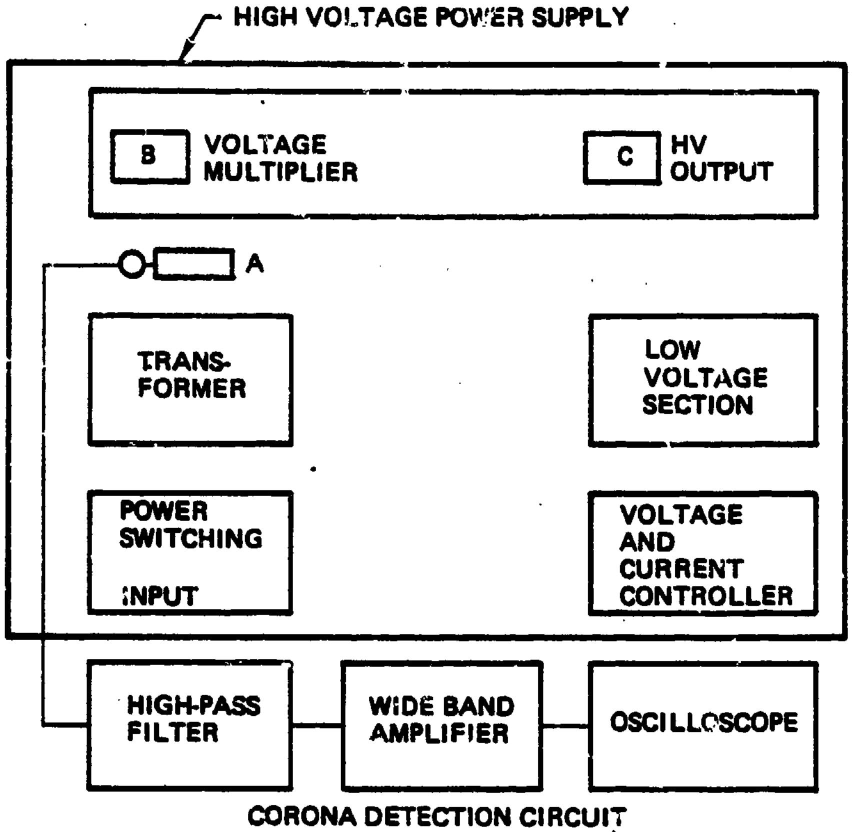


FIGURE 72: POWER SUPPLY CORONA TEST

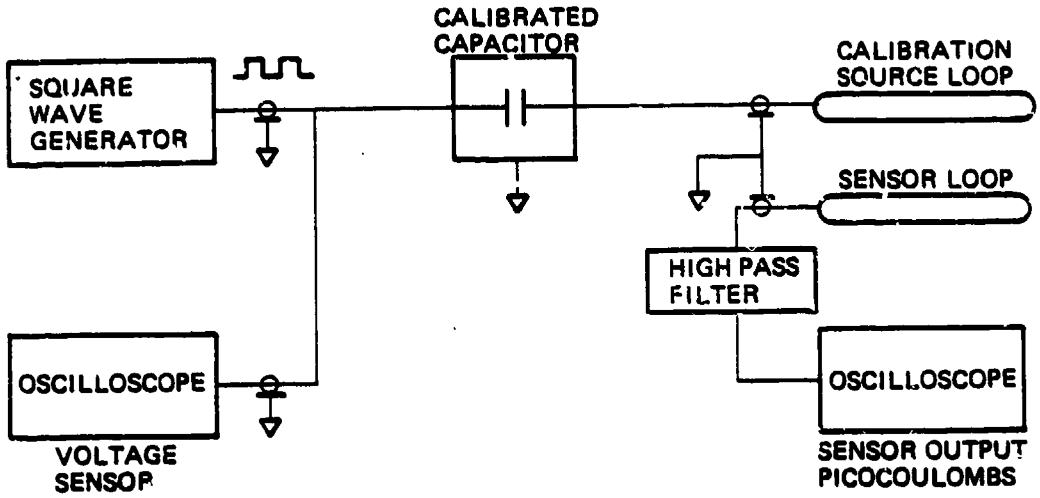


FIGURE 73: CALIBRATION EQUIPMENT

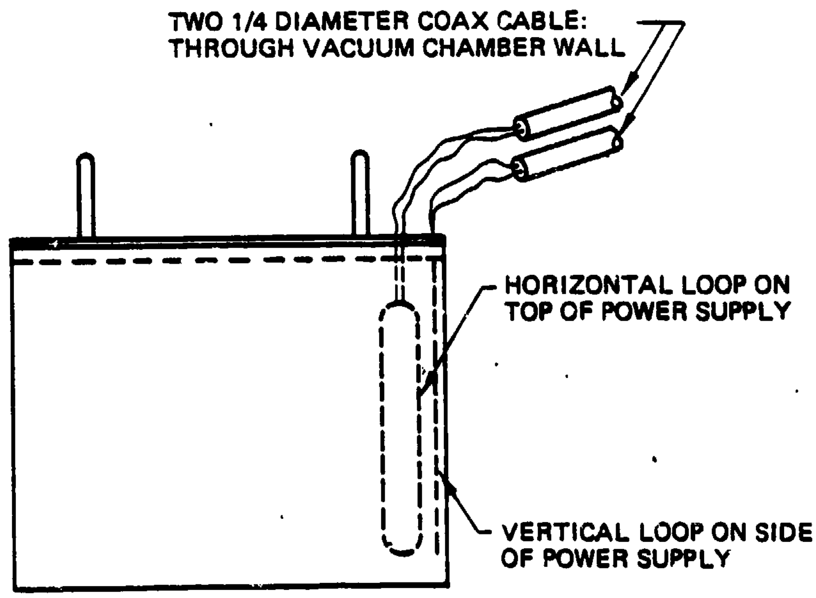
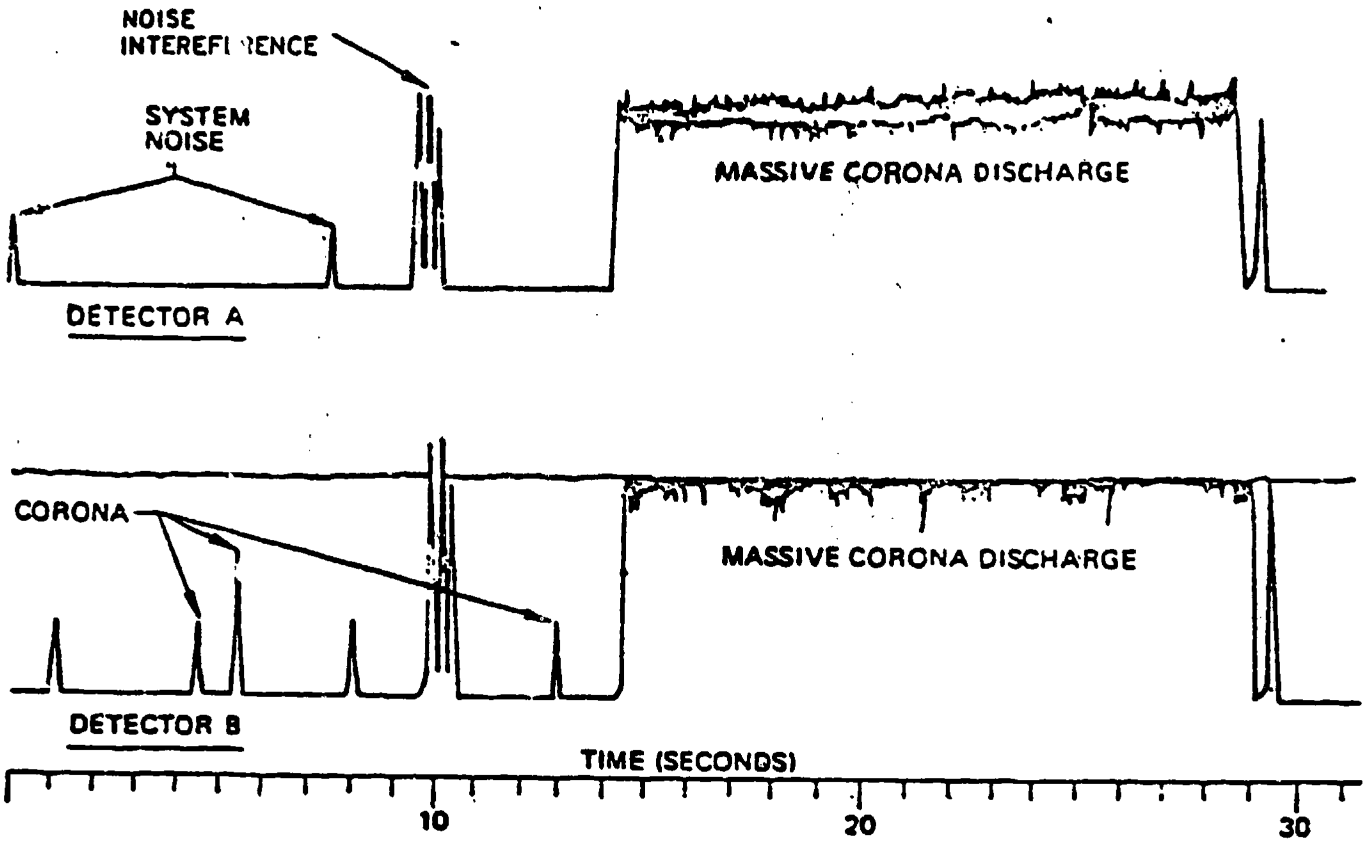
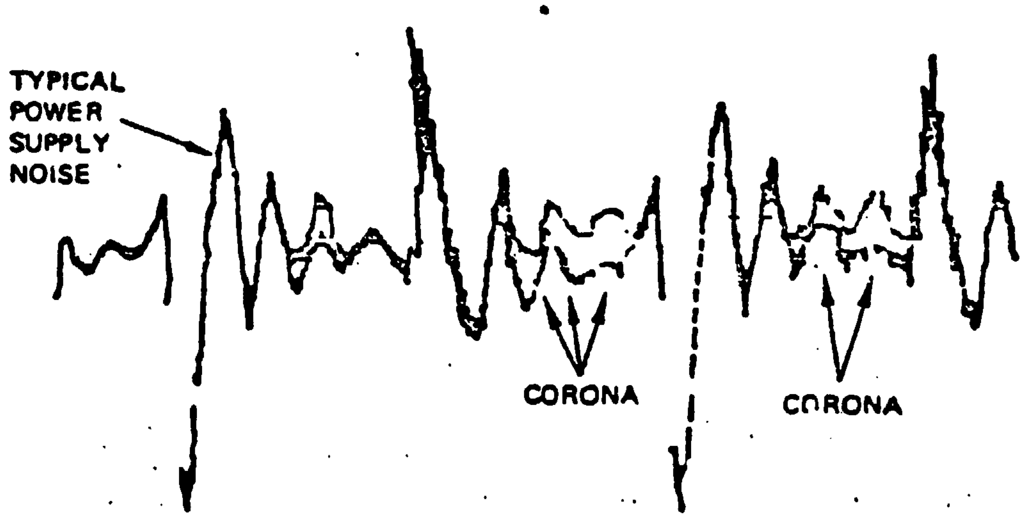


FIGURE 74: SENSOR ATTACHMENTS



NOISE AND CORONA DISCHARGES RECORDED ON AN OSCILLOGRAPH



CORONA DETECTED BY RF COIL DISPLAY ON FIBER OPTICS RECORDER

FIGURE 75. NOISE AND CORONA RECORDINGS

FIGURE 76: PARTIAL DISCHARGES
SUPERIMPOSED ON A
HIGH VOLTAGE PULSE

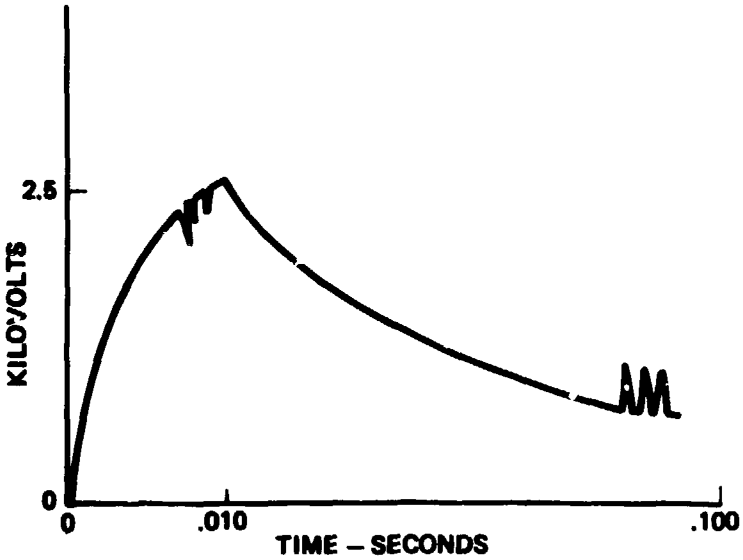


FIGURE 77: CHARGE-DISCHARGE WAVEFORM WITH CORONA

d. wiring, cabling, and connectors

Environmental test chambers can be evaluated with the same corona detection circuits and detectors as are used for airborne parts and circuits. The detectors must be capable of operating at pressurse less than 4. x 10^3 N/M^2 (30 torr). They should respond to frequencies up to 100 MHz, should be omnidirectional, and should not contaminate the chamber.

7.5.1 Contamination. The test chambers can be contaminated by foreign gasses, dust particles, oxides, salts, and out-gassing products. Helium, argon, and neon effectivity reduce the partial discharge initiation voltage. Test chambers should be purged to eliminate contaminating gases unless of course the tested unit generates or releases such gases. Helium and hydrogen will leak through ceramic and glass seals of pressurized units.

Dust particles can intensify local dielectric stress, develop tracking, and eventually form a point electrode. Oxides and salts deposited by handling during assembly, storage, transportation, or operation will degrade insulation materials. They also alter the surface composition of the electrodes.

7.5.2 Life Testing. Twenty percent overvoltage will shorten insulation life to about one-fourth of normal (Figure 65). However, in accelerated life tests the insulation must operate free of partial discharges at both normal and over-voltage levels.

Experience has shown that incorporating the following elements into a life test contributes to the development of valid test data.

a. Partial discharge detection readout should be monitored continuously by electronic means.

b. Temperature cycling is required to produce the thermo-mechanical stresses that may enhance partial discharge formation. The temperature should be cycled from minimum to the maximum extremes specified for the equipment at least five times. Each cycle should include "soak" time at each temperature extreme to permit the internal

components to thermally stabilize. These tests may be performed in either air or vacuum.

c. If partial discharges become more frequent with increasing temperature, more temperature cycles should be performed to determine whether the partial discharges increased because of temperature or time.

d. The gas pressure should be kept within the operating range of the tested equipment but at a point corresponding to the closest approach to the Paschen law minimum or highest operating altitude pressure.

e. After completion of the temperature cycling, the high voltage should be turned off and on five times at 5 minute intervals. The off time should be less than 15 seconds. During the power turn-on the partial discharge detectors should be operating and their output should be recorded. An increase in the magnitude and/or quantity of impulses for each on-off cycle indicates that insulation is deteriorating and should be replaced.

f. Life testing should follow the temperature cycling, and should continue for at least 25 percent of the expected life of the equipment.

8. QUALITY ASSURANCE PROVISIONS, SPECIFICATIONS AND STANDARDS

The most reliable tests are those which best simulate service conditions. For this reason, valid testing of the durability of materials with respect to long-time breakdown processes such as partial discharge erosion and treeing are time consuming. Attempts to accelerate such tests are unreliable since materials do not respond linearly to changes in test severity. Hence, dependable information can often be obtained only with tests extending over months or years.

A word of caution is needed about the testing for phenomena involving sparking in an altitude chamber. Sparking may not occur in the chamber, but will occur in the equipment when in service because there are free electrons in the airplane environment, but not in the test chamber. A radioactive source of ionizing radiation such as polonium should be placed near the equipment under test in the altitude chamber to insure a supply of electrons in the critical gap volumes. Polonium is recommended because it is not as hard to handle as other gamma sources like cobalt 60.

8.1 Specifications and Standards. Electrical specifications and standards have been well developed for commercial high voltage components and equipment, but not so completely developed for the military counterparts. Agencies that have developed high-voltage specifications and standards are:

- National Electrical Manufacturers Association
- Underwriters Laboratories
- American Standards Association
- Institute of Electrical and Electronic Engineers
- U.S. Department of Defense (military specifications and standards)
- Electrical Equipment Manufacturers

8.2 Military Specifications and Standards. Military specifications and standards applicable to airborne high-voltage components and equipment are listed in Tables 34 through 37. High-voltage specifications for the components tested during this program effort are in Volume II, High Voltage Testing, Specifications and Procedures.

8.3 Safety. A potential personnel shock hazard results from the "recovery charge phenomenon," where a latent charge builds up in any capacitor-like structure after it has been discharged. Therefore, high voltage connector protective caps having integral shorting contacts should be installed on all open high voltage connectors when not in use. These connector protective caps should be installed on each high voltage cable and equipment prior to shipment and should remain on until installation is complete.

TABLE 34

CAPACITORS

Specification Number	Title	Highest Voltage Rating	Highest Altitude 1
MIL-C-11693	Capacitors, Feedthrough, RFI, AC and DC	1200 Vdc	4
MIL-C-19978	Capacitors, Fixed, Plastic (Or Paper Plastic) Dielectric	1000 Vdc	4
MIL-C-39006	Capacitors, Fixed, Electrolytic, Tantalum	630 Vdc	7
MIL-C-39014	Capacitors, Fixed, Ceramic, Dielectric	1500 Vdc	5
MIL-C-39022	Capacitors, Fixed, Metalized, Paper-Plastic Film or Plastic Film Dielectric, AC & DC	600 Vdc	5
MIL-C-55514	Capacitors, Fixed, Plastic (or Metalized Plastic) Dielectric, DC	600 Vdc	5
MIL-C-83439	Capacitors, Fixed, Feedthrough, EMI, AC & DC	400 Vdc	3

1 Altitude Code

Code	Highest Applicable Altitude
1	Sea Level
2	50,000 Ft.
3	70,000 Ft.
4	80,000 Ft.
5	100,000 Ft.
6	110,000 Ft.
7	150,000 Ft.

TABLE 35

CONNECTORS

Specification Number	Title	Highest Voltage Rating	Higest Altitude
MIL-C-005015	Connectors, Electric "AN" Type	3,000 Vrms	1
MIL-C-12520	Connector, Plug and Receptacle (Electrical, Waterproof) and Accessories, General Specification for.	3,000 Vrms	1
MIL-C-26482	Connectors, Electrical, Circular, Miniature, Quick Disconnect, Environment Resisting	1,000 Vrms 450 Vrms	1 3
MIL-C-26500	Connectors, General Purpose, Electrical, Miniature, Circular, Environment Resisting, 200°C Ambient Temperature	500 Vrms 300 Vrms 300 Vrms	1 3 6
MIL-C-26518	Connectors, Electrical, Miniature, Rack and Panel Environment Resisting, 200°C Ambient Temperature	500 Vrms 300 Vrms 300 Vrms	1 3 6
MIL-C-81511	Connector, Electric, Circular, High Density, Quick Disconnect, Environment Resisting, Specification for	1000 Vrms 450 450 450	1 2 3 6
MIL-C-83723	Connector, Electric, Circular, Environment Resisting General Specification For	3000 Vrms	1
MIL-C-38999	Connectors, Electrical, Circular, Miniature, High Density, Quick Disconnect, Environment Resistant, Removable Crimp Contacts	900 Vrms	1

TABLE 36

WIRE AND CABLES

Specification Number	Title	Highest Voltage Rating	Highest Altitude
MIL-C-915	Cable, Electrical, Special Purpose, General Specification For	3,000 Vrms	1
MIL-C-3432	Cable and Wire, Electrical (Power and Control); Semi-Flexible, Flexible, and Extra Flexible, (300 and 600 volts)	600	1
MIL-W-5086	Wire, Electrical, 600 Volt, Copper, Aircraft	3,000	1
MIL-W-7072	Wire, Electric, 600-Volt, Aluminum, Aircraft, General Specification For (ASG)	600	1
MIL-C-7078	Cable, Electric, Aerospace Vehicle, General Specifications	600	1
MIL-W-7139	Wire, Electrical, Polytetrafluoro-ethylene-insulated, Copper, 600-Volt	600	1
MIL-W-8777	Wire, Electrical, Silicone Insulated, Copper, 600 Volt, 200 Deg. C	600	1
MIL-C-13777	Cable, Special Purpose, Electrical, General Specifications	600	1
MIL-W-16878	Wire, Electrical, Insulated, High Temperature	3,000	1
MIL-C-21609	Cable, Electrical, Shielded, 600-Volt	600	1
MIL-W-22759	Wire, Electric, Fluorcarbon-Insulated	1,000	1
MIL-W-25038	Wire, Electrical, High Temperature and Fire Resistant, Aircraft	600	1
MIL-C-27072	Cable, Special Purpose, Electrical Multi-conductor	3,000	1
MIL-C-55021	Cable, Twisted Pairs and Triples, Internal Hook-up	3,000	1
MIL-W-81044	Wire, Electric Cross-linked Polyalkene-Insulated Copper	600	1
MIL-W-81381	Wire, Electric, Polyimide Insulated, Copper and Copper Alloy	600	1

TABLE 37

EQUIPMENT

Specification Number	Title	Highest Voltage Rating	Highest Altitude
W-C-375	Circuit Breaker, Molded Case; Branch-Circuit and Service	600 Vrms	1
MIL-C-17361	Circuit Breaker, Air, Electric, Insulated Enclosure (Shipboard Use)	500 Vrms	1
MIL-C-17587	Circuit Breakers, Air, Electric, Open Frame, Removable Assembly (Shipboard Use)	500 Vrms	1
MIL-F-15733	Filters, Radio Interference	600 Vdc 250 Vrms	2 2
MIL-T-27	Transformers and Inductors (Audio, Power, and High Power Pulse), General Specification for	580 Vrms	3
MIL-C-15305	Coil, Radiofrequency, and Transformers, Intermediate and Radio frequency, General Specification for	200 Vrms	3
MIL-STD-451	SAFETY, Requirement 1, Paragraph 5, Electrical		

9. POSSIBLE PROBLEM AREAS AND SUGGESTED SOLUTIONS

High voltage systems are plagued with annoyances that are unnoticed in lower voltage systems. Some of the more subtle annoyances are listed below.

9.1 Debris. Small dielectric flakes or chips lodged or laying on the surface or edge of a coil will align themselves with the electric field. Secondly, they will be charged to the same potential as the surface to which they are attached acting as a point on the surface. This will decrease the utilization factor of the gas or oil and be a cause of excessive corona and eventual breakdown. Thorough cleaning with high pressure air and inspections are the cure for this problem.

9.2 Mechanical Stress. Terminations should be designed so mechanical stress points are minimized on the insulating boards. This can be accomplished by molding the terminal in a solid insulating material that is attached to the board, or by placing metal spacers with flanges through the board. The metal spacers not only reduce the mechanical stress but also increase the surface utilization factor between the flange edges.

9.3 Flexible Wiring. High voltage extra flexible wiring is acceptable in some limited cases. It should be used only as a last resort. When used, it should be guided from terminal to terminal to eliminate the probability of the wire insulation intermittently touching other surfaces containing higher or lower voltage circuits.

9.4 Manufacturing Cleanliness. No one can overstress the need for manufacturing cleanliness. When papers, films and other cleaned surfaces are handled, gloved hands should be mandatory. Slight amounts of oils or acids may be the cause of an improper bond or encapsulation. Any paper, cloth, film or other dielectric material is suspect and should be inspected by materiel, shop fabrication personnel, or engineering. Also smoke emitting objects in materials fabrication shops may contaminate the dielectric.

9.5 Mold Release Agents. Silicone products may contaminate certain epoxies, urethanes, and other insulating materials. Compatibility and contamination of materials for bonding purposes should be investigated prior to fabrication. When there is an incompatibility, then personnel working with the contaminates should be properly informed of the condition and take precautions to avoid contamination.

9.6 Similarity. Too often materials and designs are used because they have similar characteristics. Similarity ends at the last pour of a batch, the last section of the roll, and the last fabricated part by a skilled craftsman. New personnel must be informed of the hazards and precautions, the application and handling of parts and materials, and the inspection, calibrating, and testing of all jigs, tools, and assemblies in order to produce an excellent product.

9.7 Testing. Flaws in outer surfaces and between a single conductor and a surface can be visually inspected. When a coil, circuit, or multiple conductor assembly is tested, the test must be designed to include the detection of imperfections between coil layers, circuit parts, and assembly layers. This implies that the total assembly must be energized in such a way that all overstressed electrical parts will be detected. An over-voltage test and/or overfrequency tests are two methods for testing.

9.8 Environment and Life. Most high voltage circuits and parts will be installed in enclosed pressurized containers. This will reduce the probability of thermal shock, but not temperature extremes. Testing an insulation in a small dish is inadequate. Fabricated assembled parts and circuits should be assembled per specification inside the container and tested through the temperature extremes with all circuits normally energized. Five to nine cycles are recommended. Pre-environmental tests and post-environmental tests should include corona, dissipation factor, and insulation resistivity and a visual inspection for breaks, tears, and deformation. Any significant changes in appearance or electrical characteristics are reason for further testing and/or modification prior to qualification and life testing.

9.9 Tabs. Coil winders and circuit assemblers often place small tabs on wires and parts for identification and installation purposes. When these coils and circuits are to be encapsulated, film tape tabs such as mylar adhesive may be a cause for a built-in gas pockets or voids. These voids may be a place for the initiation of partial discharges and eventual voltage breakdown. When tabs are required, make them of porous materials that are compatible and easily wetted with the encapsulant.

9.10 Spacers. Spacers between two energized encapsulated units must be near void-free and have smooth or rounded surfaces to reduce tracking susceptability across the spacer surface. The two dielectrics will reduce the stress across the spacer and the available charging current but they will not eliminate the problem. The spacer surface should be designed as though the voltage at the dielectric surfaces was from base electrodes not dielectrics.

9.11 Coatings. Coated metal surfaces have higher breakdown voltage characteristics than uncoated surfaces provided the correct coating material is applied. Some coatings do not bond well, flake and reduce the electrical stress capability of the two electrodes. Others may have pin holes and voids or blisters which will also cause flaking. Coatings must be evaluated with proper materials under identical environmental and electrical stress conditions to be fully qualified.

9.12 Determining Corona Limitation Voltage. The corona initiation voltage (CIV) of an electrical apparatus can be determined when the design parameters and the applicable Paschen-law curve are known. The particular Paschen curve used depends on the type of gas the corona would occur in, the temperature of the gas, and the configuration of the electrodes.

A comparison of Paschen curves for different possible gases is given in Figure 78. The most common gas is air, of course. If the temperature exceeds 500^{o}F, special Paschen curves must be used. Several curves for insulated and noninsulated wires are given in Reference 132 and 133.

132. D-2707, "Corona Control Plan," prepared by W. G. Dunbar, D6A10256-1, The Boeing Company, 1966.

133. W. G. Dunbar, "Corona Testing of Supersonic Airplane High Temperature Wire," Eighth Electrical Insulation Conference; Number 68C6-EI-73, December 1968.

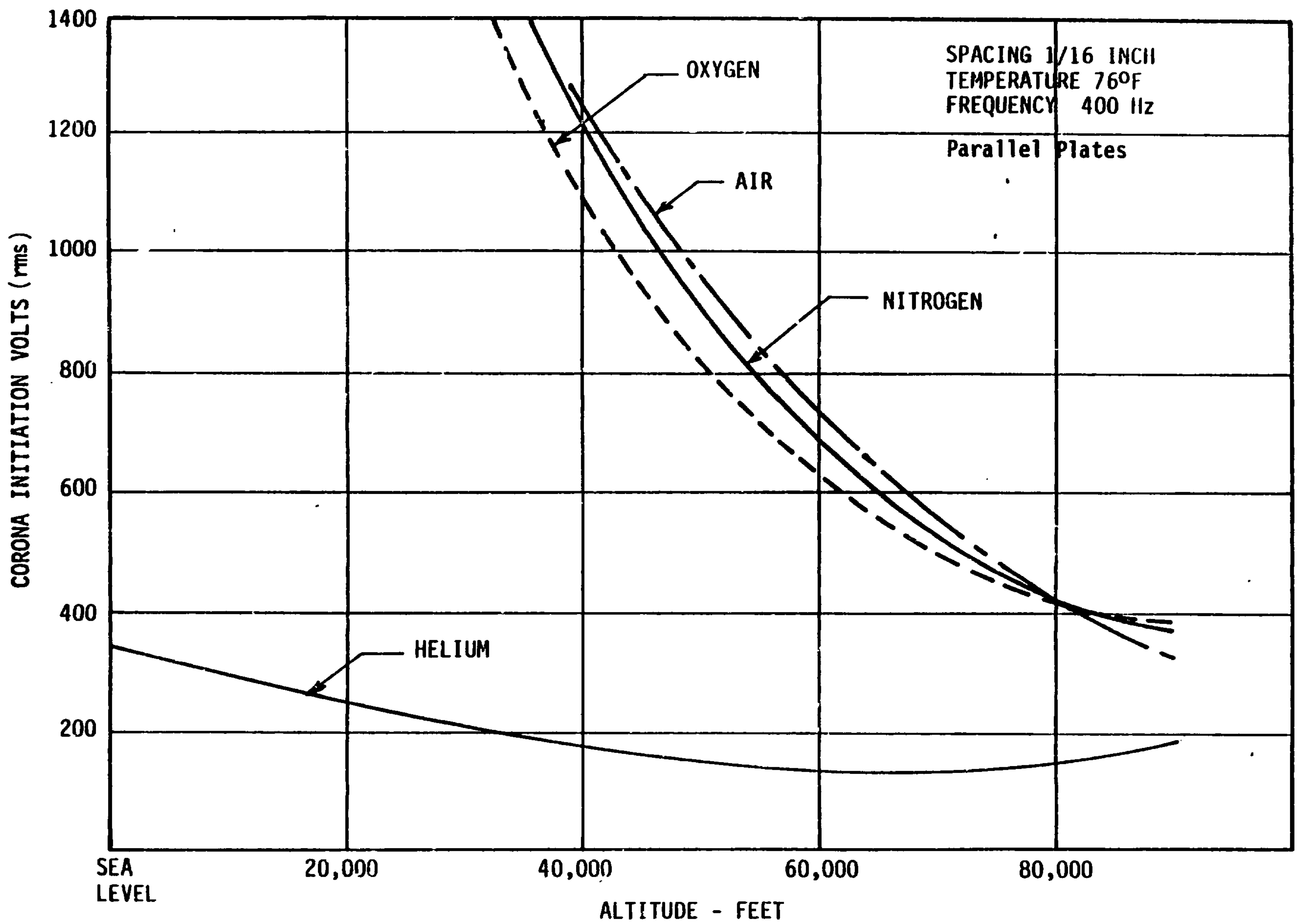


FIGURE 78. CIV OF COMMON GASES

10. CONCLUSIONS

This design guide is intended to be used by designers of compact, high density, high voltage equipment. Formulas and empirical equations are shown for typical high voltage electrode configurations found in electrical equipment. A designer using these empirical formulas and the field plotting methods shown can locate maximum field stresses within electrical insulation systems. Then the proper dielectrics can be selected for the application.

Design configurations and test methodology are described. Each design must be configured within the space and weight allocations. Thus these configurations are only guidelines. Likewise tests should be accompanied by detailed test procedures before a high voltage design is recommended for fabrication.

APPENDIX A

FIELD PLOTTING METHODS

A1. <u>Freehand Field Plotting</u>. Freehand field plotting using "curvilinear" squares is shown in this paragraph. These squares, generated by constant-potential and constant-field lines, have the following properties:

- All sides intersect at right angles.
- All "squares" can be subdivided (by an equal number of equipotential and orthogonal flux lines) into smaller squares, which more closely approach true squares as the subdivision is continued.
- Every curvilinear square has the same capacitance, and the flux per square is proportional to the potential difference across it.
- Field lines leave the conductor at right angles.

If the region is not completely enclosed by known boundary conditions, the designer needs to be sure that the field divides properly as infinite distance is approached. Combined fields from two or more sources are best dealt with by drawing each one separately and then superimposing. Most designs have symmetry that can be used advantageously to reduce the work required.

Each trial suggests changes that must be made to determine the final shape of the field. The correctness of the final field plotted by this cut-and-try process is tested by the following criteria.[113]

- Do the field lines and equipotential lines intersect everywhere at right angles?
- Are there curvilinear squares everywhere in the dielectric media, or do they become so when subdivided?

Examples of freehand flux plotting are shown in Figures A-1 and A-2. Accurate freehand plotting techniques are found in References 6, 112 113, 114, and 134 through 138. These references, though old, were used successfully for four decades before computers were available. Many designers continue to use this technique. A block diagram of a computer program for field plotting is outlined in Appendix B.

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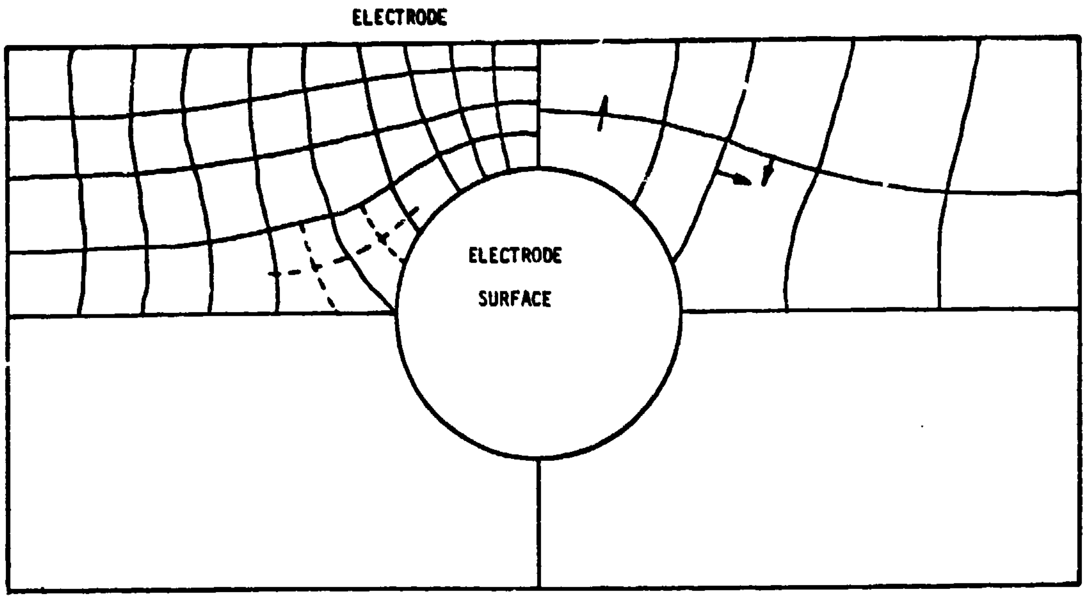

FIGURE A1. FREEHAND FIELD MAPPING

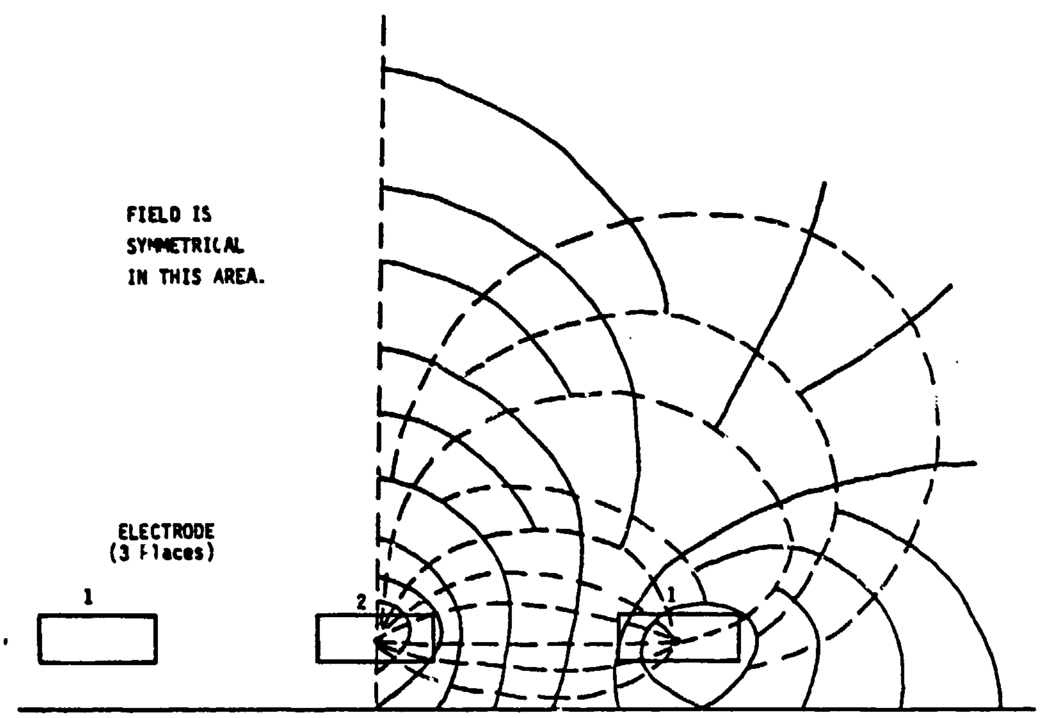

FIGURE A2. FREEHAND FIELD MAPPING

A2. Resistance Paper. A technique for mapping fields uses resistance paper, also called teledeltos paper. This method is rapid, and the plotted equipotential lines resemble a freehand field plot. Non-uniform fields generated by multiple electrodes are easily handled. Furthermore, the designer can easily change the electrode and dielectric shapes to get the highest utilization factors.

The general technique is to represent the electrode on the resistive paper with silver conducting paint. The shape and spacing of the electrodes must be scaled accurately. For best results, space the high and low-potential electrodes about 9 to 12 inches apart. Next, apply a voltage between the conducting surfaces, voltmeter and points of equal potential on the resistance paper are mapped with a terminal connected to a dull-pointed probe (Figure A-3).

In plotting the equipotential lines the voltage between electrodes is set at a convenient value, say 10 volts. The probe is placed on the paper between the electrodes, preferably where the field gradient is highest, and moved until a given voltage, say 4 volts, is read. The spot recorded with a dot using a non-conducting ink or pencil lead. The probe is moved laterally about one inch and the same 4 volts is sought. Repeating this process for additional points and at other voltages produces points through which equipotential lines can be readily plotted (Figure A-4).

Mathematically, the following has been accomplished.

- The electric field within the paper satisfies the equation

$$\nabla t \cdot \bar{E} = \nabla t \times \bar{E} = o \qquad \text{(A-1)}$$

where $$\nabla t = \bar{a}_x \frac{\partial}{\partial x} + \bar{a}_y \frac{\partial}{\partial y} \qquad \text{(A-2)}$$

- A solution to (1) is a potential function $\phi(x, y)$ in the form $\bar{E}(x, y) = -\nabla t\phi\ (x, y)$, where $\phi(x, y)$ is the point-to-point voltage measured with the meter.

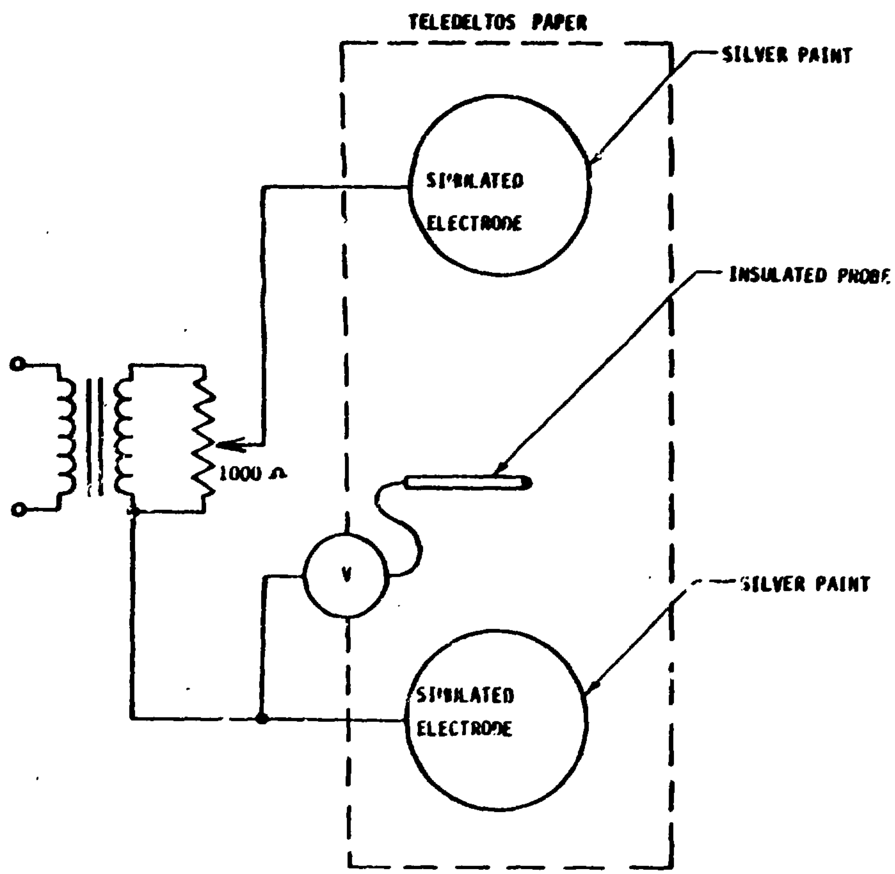

FIGURE A3. RESISTANCE PAPER PLOT CIRCUIT

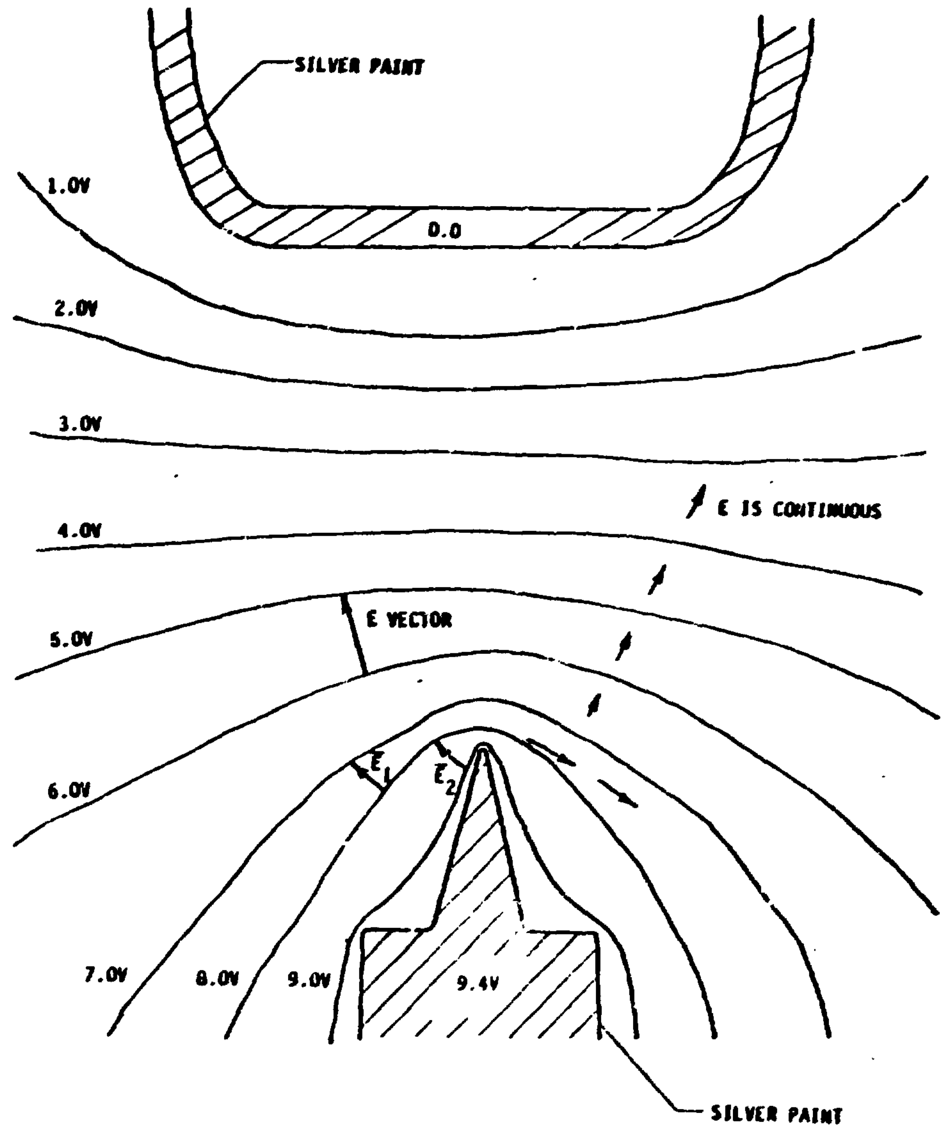

FIGURE A4. PLOT OF EQUIPOTENTIAL LINES USING RESISTANCE PAPER

- The current density within the paper, $\bar{J}$ (ampere/meter^2) and $\bar{E}$ is almost linear in the form $\bar{J}(x, y) = \sigma\bar{E}(x, y)$ where σ is the conductivity of the paper (ohms/meter^2).

The field lines, if required, can be drawn freehand by using curvilinear square principle, or can be developed by using a conjugate electrode arrangement. Freehand flux plotting is probably easier and quicker. The conjugate electrode approach requires that the probes be placed along a selected field line, and that the current flow be constant along the field line.

The field lines, once located can be superimposed upon the equipotential lines for the full plot, as shown in Figure A-2.

A3. <u>Other Field Plotting Techniques</u>. Other field plotting devices include electrolytic troughs, rubber membranes, and mathematical analyses.

<u>Electrolytic Trough</u>. A large tank contaning a weak solution of copper sulphate is the electrolyte and copper plates are the electrodes. A nickel or platinum wire probe on a pantograph is used to seek the equipotential lines between the electrodes. The detector is Wheatstone bridge having probe and electrodes on its two arms and a calibrated potentiometer as the other arm (Figure A-5).

<u>Rubber Membrane</u>. A thin rubber membrane evenly stretched over a frame can be used to plot fields. The appropriately scaled electrodes protrude upward for positive potentials and downward for negative potentials; the frame represents zero potential. The profile gives an exact replica of the equipotential lines.

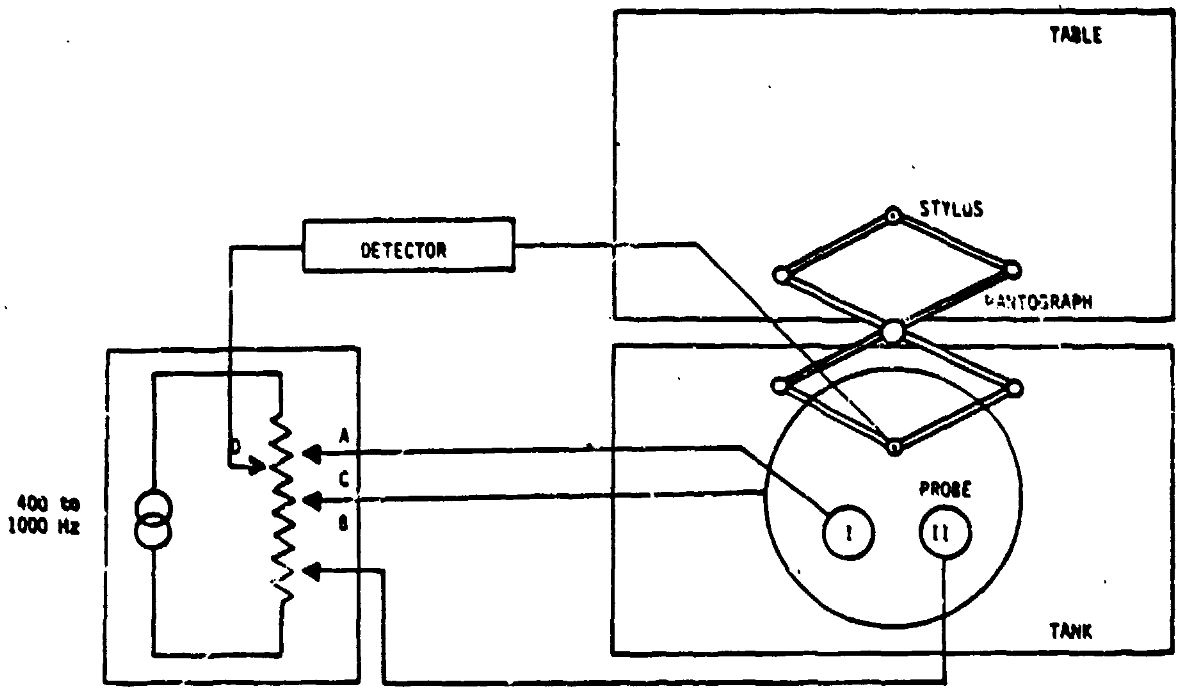

FIGURE A5. BLOCK DIAGRAM OF ELECTROLYTIC TROUGH

134) J.F. Calvert and A.M. Harrison, "Graphical Fluid Mapping," Electric Journal, Vol. 25, March 1928.

135) A.D. Moore, "Mapping Magnetic and Electrostatic Fields," Electric Journal, Vol. 23, 1926, p. 355-362.

136) A.R. Stevens, "Fundamental Theory of Fluid Plotting," General Electric Review, Vol. 29, November 1926, pp. 794-804.

137) R.W. Wieseman, "Graphical Determination of Magnetic Fields-Practical Applications," AIEE Trans., Vol. XLVI, 1927, p. 141.

138) H. Poritsky, "Graphical Field Plotting Methods in Engineering," AIEE Trans., Vol. 57, 1938, p. 727.

APPENDIX B

INTRODUCTION

There are several numerical solutions to the Laplacian equation:

$$\nabla^2\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \qquad \text{(B1)}$$

Before high-speed computers witn large memories became available, the usual numerical solutions were not practical because of the many computations required.

Galloway, Ryan, Eng, Scott, and Mattingly [139] of Reyrolle Parsons Ltd., England, have developed computer programs using finite-difference equations, and the Gaussian forward-elimination and back-substitution for solution of these finite difference equations (B1, B2, B3, B4). This system of programs is easily adaptable to problems in two dimensions, or three dimensions with one axis of symmetry.[140, 141, 142]

A charge simulation method adaptable to computer solutions was presented by Singer, Steinbigler, and Weiss.[143] Charge simulation methods do not need large computer storage and long computation times. Using Gauss' theorem, Misaki, Yamamoto, and Itaka determined the electrostatic potential field distribution for a three dimensional asymmetric problem in circular cylindrical coordinates.[144]

Finite Difference Technique. The numerical method presented here is characterized by a representation of the electrostatic potential field distribution with discrete nodal points. Finite difference equations are determined for each nodal point. The composite of all the finite difference equations is solved by an iteration technique called successive over-relaxation.[145] This yields the electrostatic potential for each nodal point. This method of solution has been used by Storey and Billings.[146, 147] It is adaptable to field problems with single or multidielectrics, several conductors of different potential, to two and three dimensions and in cartesian or circular cylindrical coordinate systems.

To use finite difference equations to solve the Laplacian equation, the field problem is overlayed with a fine grid. The spacing between grid lines

making up the grid can vary. For accuracy and resolution, the grid lines are spaced closer together at the specific areas of interest in the field and wider apart elsewhere. Conducting surfaces and dielectric interfaces can be represented by grid lines, by diagonals between nodal points, or by triangulation of the grid lines.[148] Figure B-1 shows an example problem.

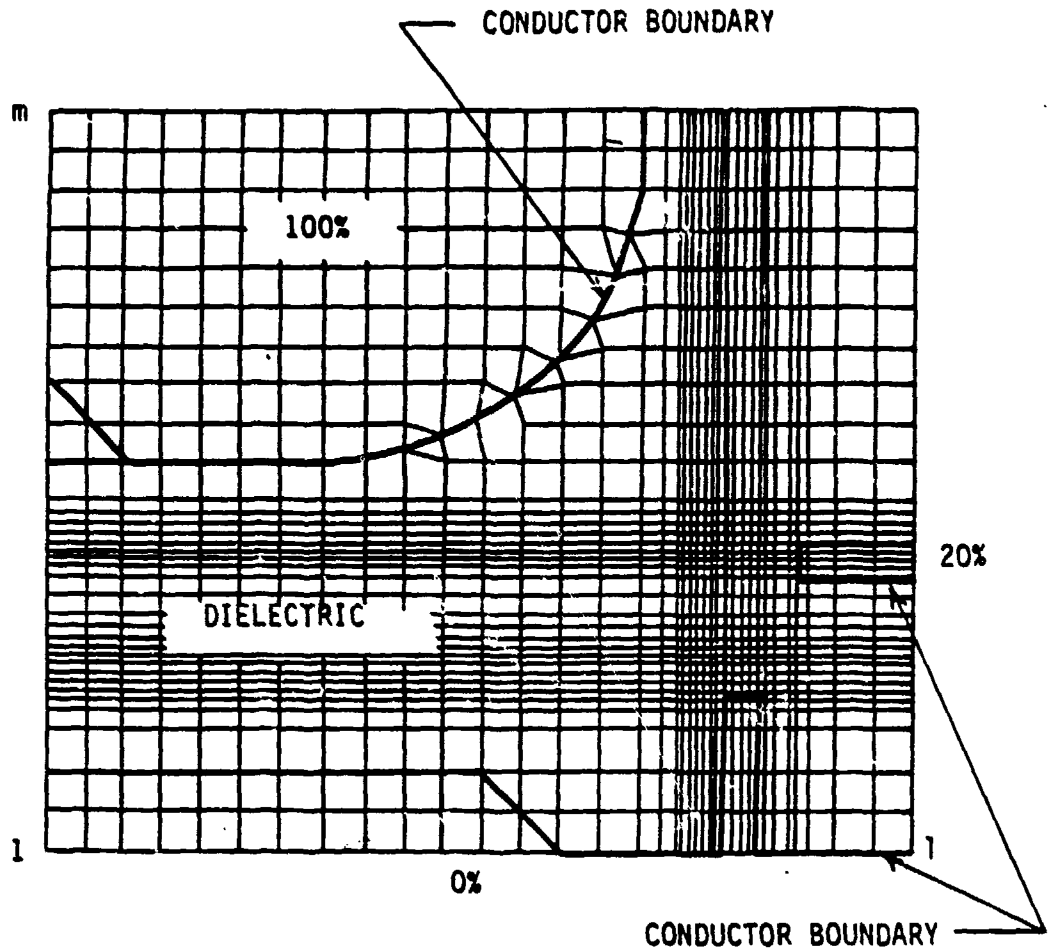

FIGURE B-1. FINITE DIFFERENCE GRID. POTENTIALS GIVEN AS PERCENTAGE OF NOMINAL TEST VOLTAGE

There are present methods of automatic grid generation which are a great aid to triangulation fitting.

Depending on the configuration of the problem, the optimal finite difference equation may be called out for use in the program. The finite difference equations are derived from Taylor's series expansion. Figure B-2 shows a

general 2-dimensional irregular star which represents one node on the grid and its immediate surrounding nodal-points. Using Taylor's series expansion in the x direction at the node (x, y), yields:

$$\phi(x-1,\ y) = \phi(x,\ y) + h_{xx}\frac{\partial\phi}{\partial x} + \frac{h^2_{xx}}{2!}\frac{\partial^2\phi}{x^2} + \text{---} \tag{B-2}$$

and $$\phi(x-1,\ y) = \phi(x,\ y) - h_x\frac{\partial\phi}{\partial x} + \frac{h^2_x}{2!}\frac{\partial^2\phi}{\partial x} - \text{--} \tag{B-3}$$

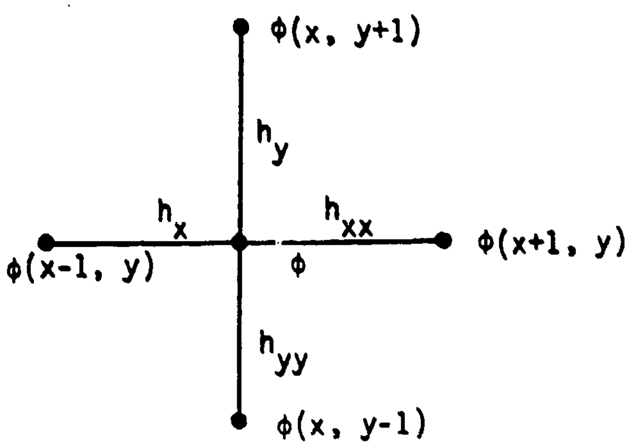

FIGURE B-2. IRREGULAR STAR IN TWO DIMENSIONAL CARTESIAN CO-ORIGINATES

Adding equation 2 multiplied by h_x to equation 3 multiplied by h_{xx} gives:

$$h_x\phi(x + 1,\ y) + h_{xx}\phi(x - 1,\ y) = (h_x + h_{xx})\ \phi(x,\ y) + \frac{h_x h_{xx}}{2}(h_x + h_{xx})\frac{\partial^2\phi}{\partial y^2} \tag{B-4}$$

Solving for $\frac{\partial^2\phi}{\partial x^2}$, and similarly for $\frac{\partial^2\phi}{\partial y^2}$, then

Substituting into equation (1) yields

$$\left(\frac{1}{h_x + h_{xx}} + \frac{1}{h_y + h_{yy}}\right)\phi(x, y) = \frac{h_x\phi(x+1, y) + h_{xx}\phi(x - 1, y)}{h_x h_{xx}(h_x + h_{xx})} + \tag{B-5}$$

$$\frac{h_y\phi(x, y+1) + h_{yy}(x, y - 1)}{h_y h_{yy}(h_y + h_{yy})}$$

which is the finite difference form of the Laplacian equation in two-dimensional Cartesian co-ordinates.

Referring to Figure B-3, the three dimensional finite difference form of the Lapacian equation in Cartesian co-ordinates is:[127]

$$\left(\frac{1}{h_x+h_{xx}} + \frac{1}{h_y+h_{yy}} + \frac{1}{h_z+h_{zz}}\right) \phi(x, y, z) = \frac{h_x\phi(x+1, y, z) + h_{xx}\phi(x-1, y, z)}{h_x h_{xx}(h_x + h_{xx})} +$$

$$\frac{h_y\phi(x, y+1, z) + h_{yy}\phi(x, y-1, z)}{h_y h_{yy}(h_y + h_{yy})} + \frac{h_z\phi(x, y, z+1) + h_{zz}\phi(x, y, z-1)}{h_z h_{zz}(h_x + h_{zz})} \tag{B-6}$$

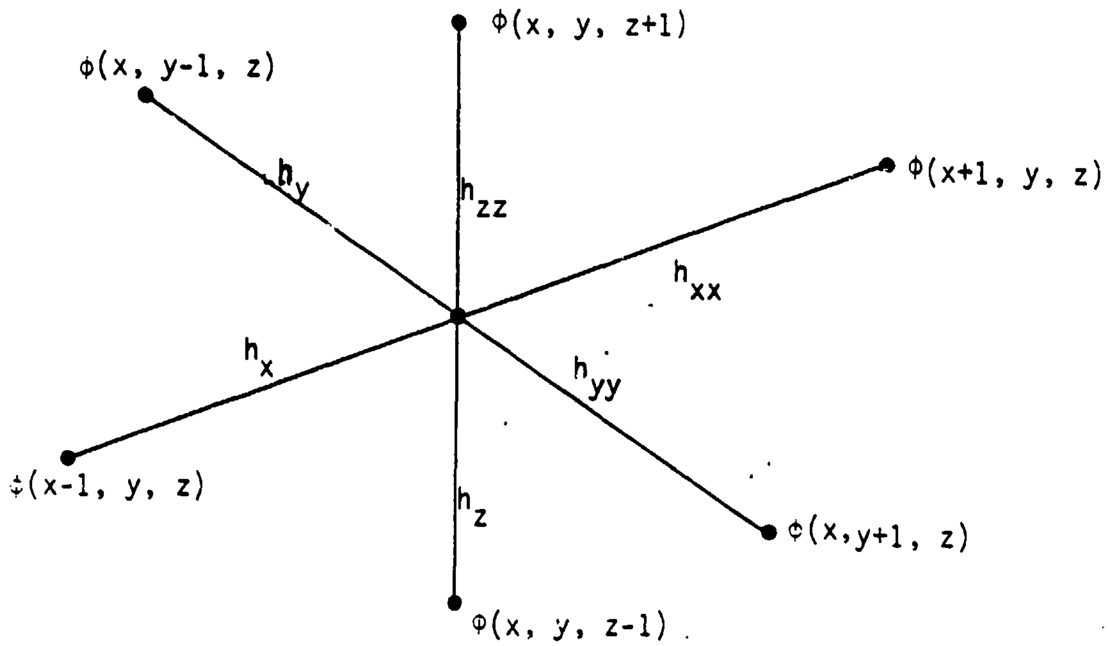

FIGURE B-3. IRREGULAR STAR IN THREE-DIMENSIONAL CARTESIAN CO-ORDINATES

Referring to Figure B-4, the three-dimensional finite difference form in circular cylindrical co-ordinates is:

$$\phi(r, z, \theta)\left(\frac{1}{\Delta_{rr}\Delta_r} + \frac{1}{\Delta_{zz}\Delta_z} + \frac{1}{\Delta_{\theta\theta}\Delta_\theta R_o^2}\right) =$$

$$\frac{\phi(r+1, z, \theta)\left(\frac{1}{\Delta_{rr}} + \frac{1}{2R_o}\right) + \phi(r-1, z, \theta)\left(\frac{1}{\Delta_{rr}} - \frac{1}{2R_o}\right)}{\Delta_{rr} + \Delta_r} + \tag{B-7}$$

$$\frac{\phi(r, z+1, \theta)\left(\frac{1}{\Delta_{zz}}\right) + \phi(r, z-1, \theta)\left(\frac{1}{\Delta_z}\right)}{\Delta_{zz} + \Delta_z} + \frac{\phi(r, z, \theta+1)\left(\frac{1}{\Delta_{\theta\theta}}\right) + \phi(r, z, \theta-1)\left(\frac{1}{\Delta_\theta}\right)}{R_o^2(\Delta_{\theta\theta} + \Delta_\theta)}$$

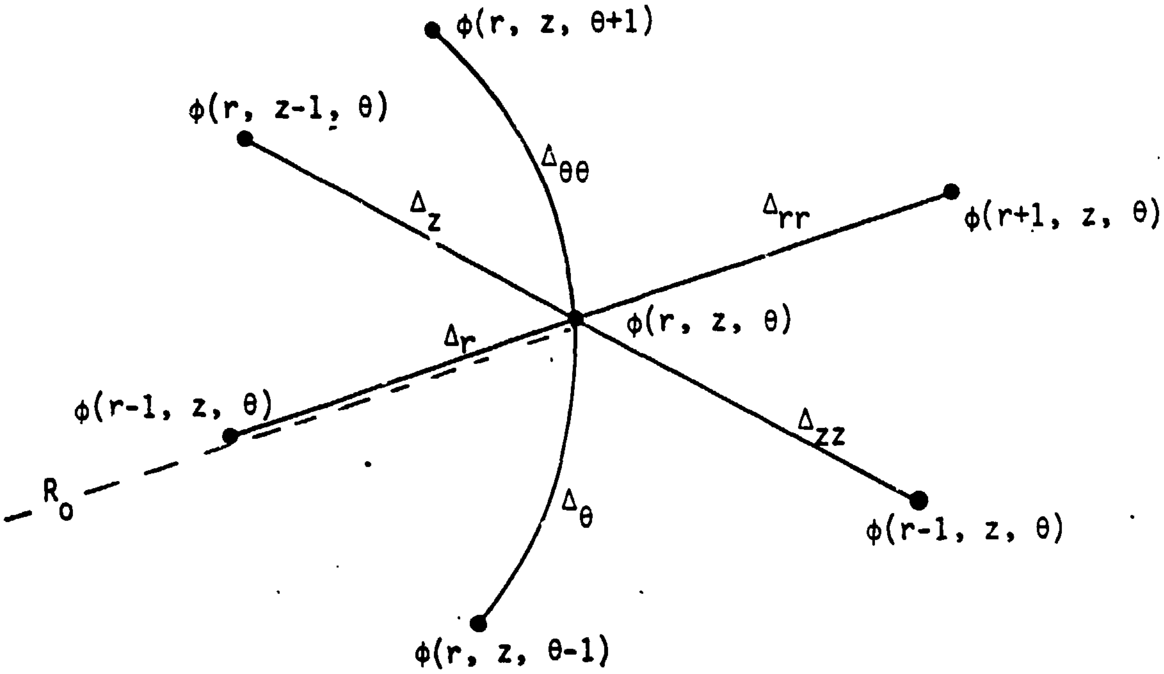

FIGURE B-4. IRREGULAR STAR IN CIRCULAR CYLINDRICAL CO-ORDINATES

Finite difference equations in Cartesian co-oridnates for multiple dielectric systems were developed for two and for three dimensions with one axis of symmetry by Galloway, Ryan, Eng, and Scott.[134] Storey and Billings,[146] and Misaki, Yamamoto, and Itaka,[144] also present techniques for determining finite difference solutions in three-dimensional, asymmetric, multiple dielectric systems.

Successive Over-Relaxation Iteration. To solve the matrix of finite difference equations, successive over-relaxation (SOR) iteration is implemented by using a positive acceleration factor with a Gauss-Seidel iteration.[149] The finite difference equation for three-dimensional Cartesian co-ordinates is presented as:

$$\phi(x, y, z)^{n+1} = \phi(x, y, z)^{n} + (\tfrac{\alpha}{k})\Big[k_x\{h_x\phi(x+1, y, z)^{n} + h_{xx}\phi(x-1, y, z)^{n+1}\}$$

$$+ k_y\{h_y\phi(x, y+1, z)^{n} + h_{yy}\phi(x, y-1, z)^{n+1}\} \qquad \text{(B-8)}$$

$$+ k_z\{h_z\phi(x, y, z+1)^{n} + h_{zz}\phi(x, y, z-1)^{n+1}\} - k\phi(x, y, z)^{n}\Big]$$

where $k = \frac{1}{h_x h_{xx}} + \frac{1}{h_y h_{yy}} + \frac{1}{h_z h_{zz}}$ and $k_i = \frac{1}{h_i h_{ii}(h_i + h_{ii})}$ where $i = x, y, z$

It is important that the optimum value (between 1 and 2) for the acceleration factor (α) be used.[145,147] The optimum value for α is different for every problem. For problems with many nodes, the following simplified expressions may be used. For a rectangular grid with 1 x m nodes

$$\alpha \text{ optimum} = 2\left[1-\pi\left(\frac{1}{(1-1)^2} + \frac{1}{(n-1)^2}\right)^{\frac{1}{2}}\right] \qquad \text{(B-9)}$$

For a square grid with 1 node per side α optimum $= \frac{2}{1 + \sin(\pi/1 - 1)}$.

During the first two iterations, α is taken to be unity.[150]

Potential Gradient. Two methods for potential gradient computation are (1) a quadratic method which is recommended for general use on all grid notes and (2) a more precise differences method for use at specific regions of interest.[142]

The quatratic method is performed by fitting quadratic equations to the potential values at adjacent points; i.e.,

$$\begin{aligned} \phi_1 &= ax_1^2 + bx_1 + c \\ \phi_2 &= ax_2^2 + bx_2 + c \qquad \text{(B-10)} \\ \phi_3 &= ax_3^2 + bx_3 + c \end{aligned}$$

The three equations (11) are solved to give values of a and b which are then substituted into the equation for the x-direction gradient

$$E_x = -\frac{\delta\phi}{\delta x} = -(2ax + b) \qquad \text{(B-11)}$$

Equations of (11) and (12) are determined for each direction and the results yield magnitude and angle of the potential gradient.

The difference method utilizes the forward-difference operator Δ, the central-difference operator δ, and the backward-difference operator ∇.[142, 145, 147] It incorporates potentials of other nodes in each direction and like the quadratic method computes the potential gradient in each direction. However, the difference method uses many more node potentials, rather than the three for the quadratic method.

The gradient error using the quadratic method is typically less than 2% and using the difference method is typically less than 0.2%.[142]

Computer Programs. Many computer programs are available for solving electric and magnetic field configurations. Many programs are designed for specific applications such as capacitor design, generator coils, transmission lines or high-frequency cavities. General and specialized programs are listed below.

General programs:

- o Two and three dimensional programs; References 151, 152, 154, 157
- o A model based on the Townsend gas breakdown; reference 153
- o Fields within electrical machines; reference 155
- o Transformer; reference 156
- o Capacitor dielectrics; reference 158
- o High Voltage insulators; reference 159

Summary. The numerical method presented gives a practical solution to potential field problems which cannot be represented by standard electrodes and dielectrics. Field distribution can be determined in two dimensions and three dimensions. Important parameters can be obtained such as potential field lines, and potential gradients in magnitude and phase. Errors in the potentials are typically less than 0.5%.

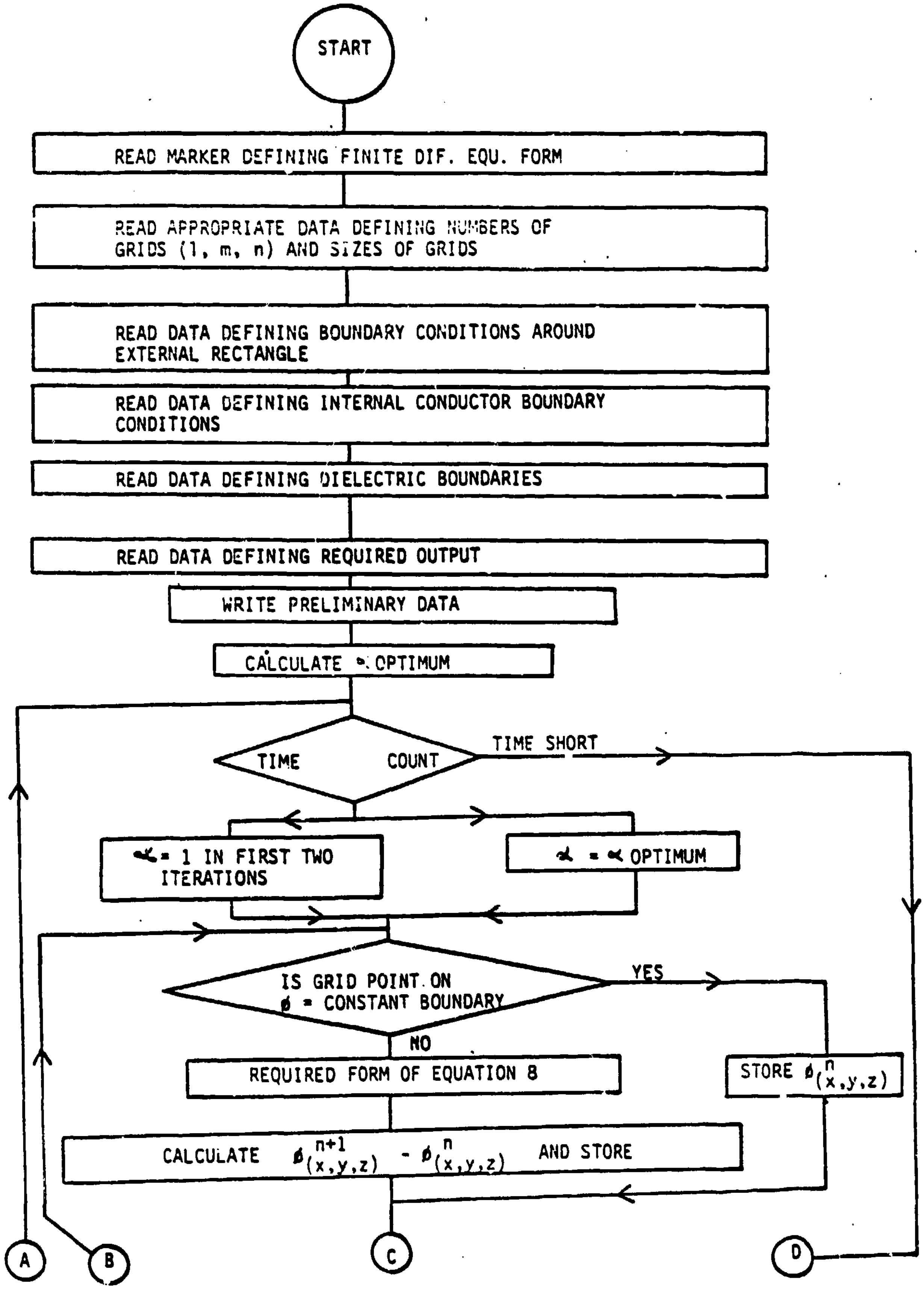

FIGURE B-5. COMPUTER PROGRAM FLOW CHART

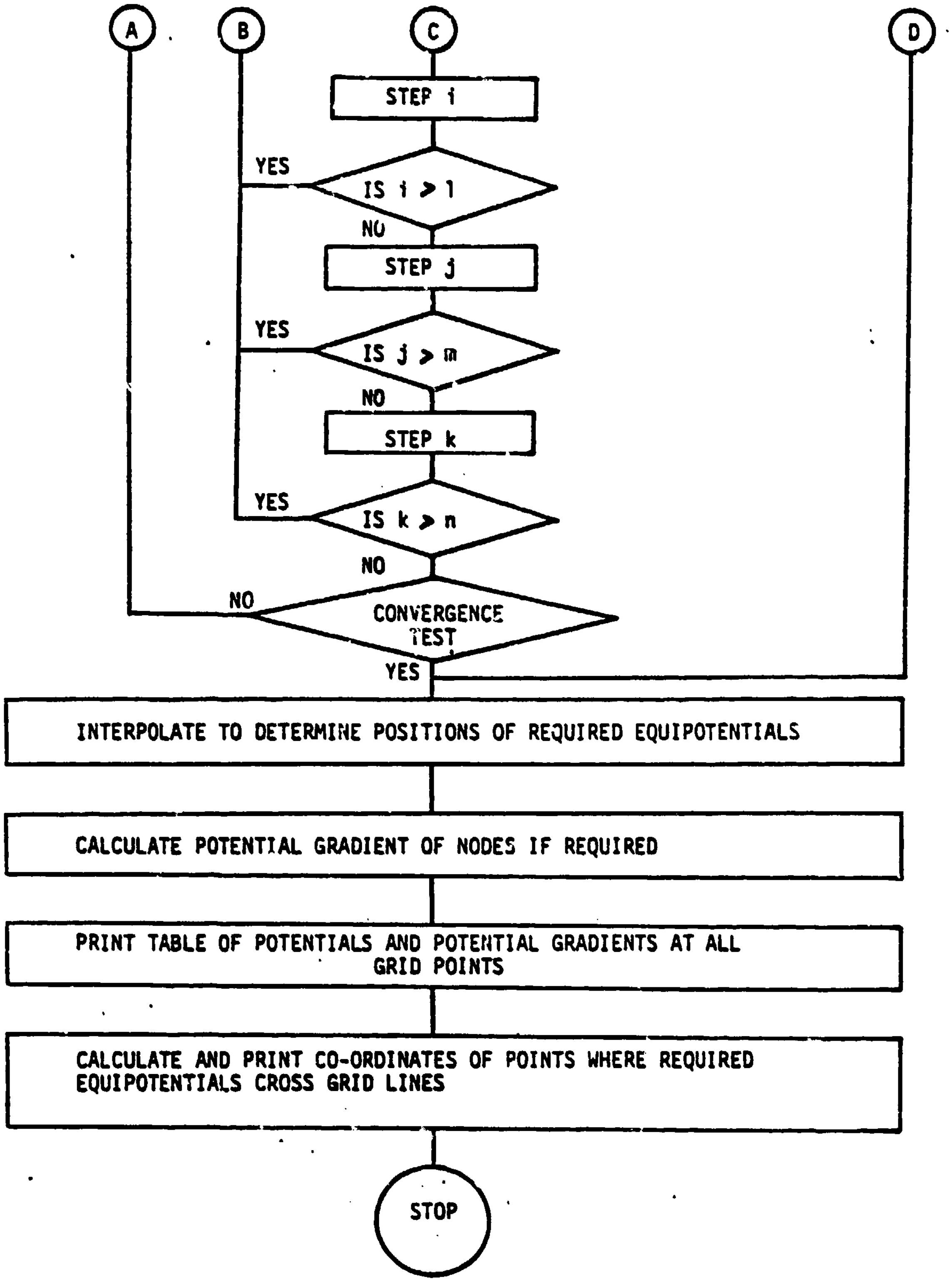

FIGURE B-5. COMPUTER PROGRAM FLOW CHART (Continued)

LIST OF SYMBOLS

ϕ = potential

ε = permittivity

E = potential gradient

R_0 = distance of any node from axis of symmetry

h_i, h_{ii} = mesh length for Cartesian co-ordinate system

Δ_i, Δ_{ii} = mesh length for circular cylindrical co-ordinate system

r, z, θ = circular cylindrical co-ordinates

x, y, z = Cartesian co-ordinates

α = acceleration factor

a,b,c,A,C = constants

l,m,n = constants governing size of region of solution

i,j,k = constants

Δ, δ, ∇ = forward-difference operator, central-difference operator, and backward-difference operator

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